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Rooftop HVAC Fault Detection and Diagnostics:

Technology and Market Review

Energy and Demand Savings Estimates

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This work is supported through the California Energy Commission's
Public Interest Energy Research Program

The CEC is in the process of reviewing this final report nbi new buildings institute

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PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Renewable Energy Technologies
- Transportation

Rooftop HVAC Fault Detection and Diagnostics: New Technologies and Standards for Energy Reduction, by the Western Cooling Efficiency Center, is an interim deliverable for the *Fault Detection and Diagnostics: Moving the Market and Informing Standards in California Project.* The project is a portion of the Evidence-based Design and Operations Program conducted by New Buildings Institute (contract number 500-08-049). The information from this project contributes to PIER's Buildings End-Use Energy Efficiency Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

In this report we identify nine different potential approaches to prioritizing FDD tools, depending on the type of data collected (air side, refrigerant side, or electrical) and the type of model used for comparison with measurements (first principles, qualitative, history). We also identify the specific criteria that must be met to have a measure that is appropriate for inclusion in Title 24. These criteria include significant energy savings, cost effectiveness, prevalence of the fault being detected, probability that the fault will be fixed, reliability of detection, deployability, and other maintenance benefits.

Keywords: Rooftop unit, air conditioning, fault detection, diagnostics, FDD, Title 24, energy standards.

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INTRODUCTION

The goal of this research is to identify the minimum requirements for FDD, including communications options for RTUs that enable cost-effective energy/demand savings. To do this, the research team undertook a comprehensive review of available products, services, and facility management behaviors related to heating, ventilation, and air conditioning (HVAC) operations/maintenance to identify and prioritize the faults that can be detected by a set of currently (or shortly) available diagnostic tools, and to evaluate the available tools. This work is the foundation for defining the minimum FDD requirements that were proposed, vetted with stakeholders, modified, and ultimately adopted into the 2013 Title 24 California Standards.

The Problem

Rooftop packaged air conditioners (RTUs) rarely receive regular preventative maintenance. Generally, service calls are limited to emergency response for major system failures that impact occupant comfort. Even in the case of equipment maintained under service contracts, technicians will only detect severe and obvious faults since their procedures typically only involve routine qualitative assessments. This means that non-emergency faults that cause significant energy waste can go unnoticed for years.

The Solution

Fault detection and diagnostics (FDD) for RTUs is a developing class of products designed to monitor RTU performance so that faults can be identified and corrected. FDD technology senses key system operating parameters, detects performance degradation, and triggers an alarm that is communicated to some form of fault management tool, the zone thermostat, or appropriate facility personnel. FDDs help to maximize the value of investments in energy efficiency systems, extend the life of RTUs, and reduce emissions.

California's Energy Efficiency Strategic Plan urges the broader application of this technology. California's proposed 2013 Energy Efficiency Standard for Nonresidential Buildings — Title 24 requirements would include FDD as a mandatory measure for all new commercial RTUs.

Purpose of This Report

Remote and automated FDD tools have the potential to save considerable energy in California's fleet of existing commercial RTUs. However, the market for these FDD systems has not yet materialized. Tools have been available for larger systems for some time, although even these have not enjoyed a significant market share. In RTUs, there are fewer tools available, and little to no market share.

Since RTUs cool over 60 percent of the commercial square footage in California and the U.S.[1], they are a significant source of energy consumption and peak demand. Under the best of circumstances, RTUs are not as efficient as larger built-up systems. However, in reality, they are

[1] W. Wang, et. al. PNNL December 2011, Energy *Savings and Economics of Advanced Control Strategies for Packaged Air-Conditioning Units with Gas Heat*, pg. vi

even less efficient. Many market failures have led to a lack of quality in the installation and maintenance of these units, and their performance is suffering. Most RTUs have one or more faults that increase their use of energy. If these faults could be found and addressed, then significant energy savings could be realized.

This report presents the results of research and analysis conducted to determine whether the environmental and cost benefits of FDD technology warrant the proposed inclusion of FDD as a mandatory measure in new Title 24 requirements.

The report:

- Describes the methodology used to collect and analyze data about FDDs
- Discusses the analysis and results of the FDD research
- Lists the availability of FDD products currently on the market or under development
- Describes potential faults found in RTU system performance and the assumptions used to model the impacts of these faults
- Discusses the probability of fault occurrence
- Lists the projected energy savings that potentially could be realized when FDD is used to detect the most common faults
- Discusses potential maintenance cost savings that potentially could be realized through FDD
- Concludes with a listing of the cost-effectiveness of FDD relative to RTU size

Summary of Research Conducted for This Report

This report is a part of the Public Interest Energy Research (PIER) project *Fault Detection and Diagnostics - Moving the Market and Informing Standards in California* within the PIER Program Evidence-based Design and Operations. The work presented here occurred from fall 2010 through spring 2012.

The overall project approach involved four phases of work and related outcomes:

Phase I (Appendix Report A: FDD Stakeholder Interviews)

- Obtained input from industry stakeholders on desired capabilities of FDD tools and service models for making best use of FDD tools.

Phase II (This Report: Rooftop HVAC Fault Detection and Diagnostics: New Technologies and Standards for Energy Reduction)

- Identified the faults that occur in RTUs and their impact and frequency to estimate the degree of savings made possible by FDD tools.
- Prioritized those faults to determine which are most likely to be cost-effectively diagnosed and addressed.

- Identified diagnostic approaches that can be used to detect these faults.
- Defined a set of criteria for the attributes an approach must have to be likely to be successful in the market place or to be successfully implemented in California's Title 24 energy code.
- Evaluated the potential approaches according to these criteria, described the currently available tools that utilize these approaches, and discussed the energy and demand savings potential of these approaches.

Phase III (Appendix Report B: FDD Energy and Demand Savings)

- Created a "Minimum FDD Capability Requirements" document that summarizes and describes the requirements for a tool that could be incorporated in Title 24, including a description of the required functionality and an outline of the acceptance tests that would be required to document installed functionality.
- Held an Industry Roundtables to obtain stakeholder feedback.

Phase IV (Appendix Report C: Title 24 FDD Standard)

- Developed and submitted a code proposal in conjunction with the Codes and Standards Enhancement (CASE) project, and participated in the Energy Commission's process for supporting the proposal.

Report Organization

This report starts by describing the faults that affect RTUs in terms of their frequency and their potential for energy savings. A set of criteria are then proposed by which the approaches are evaluated. The report then describes and classifies various approaches to detecting faults, providing examples of existing tools where available. Finally, a set of prioritized approaches is identified, which helped guide the development of a set of minimum attributes of FDD tools in the Title 24 proposal.

The Appendices contain the following work representing the additional research phases:

A. FDD Stakeholder Interviews

B. FDD Energy and Demand Savings

C. Title 24 FDD Standard: Development Method and Final Language

FAULTS AFFECTING RTUS

This section describes the different faults affecting RTUs and presents data regarding the prevalence of these faults and their energy efficiency impact.

The information in this section regarding the prevalence of faults is quoted from Cowan, NBI, 2004, "Review of Recent Commercial Roof Top Unit Field Studies in the Pacific Northwest and California." This study gathered data from previously completed research projects. Slightly over 500 units in 181 locations in California and the northwest were inspected during these different field studies, resulting in a very relevant set of data for the report's purpose. These data are shown in Table 1.

Table 1: Frequency of Some Common Faults in Rooftop Air Conditioners (Cowan 2004)

Fault	Fault Level	Frequency Found
Economizer Malfunction	Various faults	64%
Refrigerant Undercharge/Overcharge	>5%	46%
Inadequate Airflow	<300 CFM/ton	42%
Failed Sensors	Various faults	20%

The information regarding the *energy impact* of each fault comes from Breuker and Braun, 1998, "Common Faults and their Impact for Rooftop Air Conditioners." In this study, different common faults were artificially introduced in an RTU and the impact on energy efficiency and cooefficient of performance (COP) was evaluated. Table 2 shows Breuker and Braun's findings.

Table 2: Energy Impacts of Some Common Faults in Rooftop Air Conditioners (Breuker and Braun 1998)

Fault	Fault Level	% Change in capacity	% Change in COP
Compressor Valve Leakage	35% $\Delta\eta_v$	-21.3	-23.8
Condenser Coil Fouling	35% are blocked	-21.3	-23.8
Inadequate Airflow	36% Δ airflow	-19.4	-17.4
Liquid Line Restriction	20 ΔP	-17.2	-8.7
Refrigerant Undercharge/Overcharge	14% undercharge	-8	-4.6
Economizer Malfunction			Up to 40%
Thermostat Errors			Up to 40%
Failed Sensor			Up to 40%

Mechanical Faults

Compressor valve leakage

When slugs of liquid refrigerant enter the compressor, the compressor valves can be damaged. If the sealing becomes less effective, high pressure refrigerant can either:

- Leak back into the suction line across the suction valve, or
- Leak back into the cylinder across the discharge valve.

This corresponds to a loss of volumetric efficiency, the impacts of which on efficiency and COP were evaluated by Breuker and Braun in 1998.

Compressor valve leakage faults are caused by a buildup of debris on the condenser coil. This buildup limits the available condenser coil area and reduces heat transfer and the total airflow across the coil.

This is caused by a buildup of debris on the evaporator coil or other restrictions in the air path. The consequences are twofold: the airflow across the evaporator is reduced, and the heat exchange efficiency is limited. The impact of the second effect is limited, however.

Airflow has been found to be deficient in 42 percent of the cases. The following criterion has been used: the airflow is considered too low, under 300 cubic feet per minute (CFM)/ton, to be compared with the 400 CFM/ton used for industry efficiency ratings.

This fault occurs when a filter/dryer or expansion device is obstructed by debris, which increases the total pressure loss in the liquid line.

This fault can either be caused by a slow leak in the system or by the wrong amount of refrigerant introduced into the system. Charge assessment is not straightforward, and the different methods available and contractor practices explain that this is a very common problem in the field.

In the documented sample, 46 percent of units present a charge outside of a ±5 percent acceptance range. Energy savings impacts found by Breuker and Braun were up to about 5 percent for a 15 percent error in charge. Other researchers looked at higher levels of charge error, and found even greater energy impacts. For example, Robert Mowris recently tested a residential air conditioner and found upward of 65 percent efficiency loss in a unit that was 40 percent undercharged (personal communication with Robert Mowris, 2010). Regardless of the energy savings, the greenhouse gas reduction potential of detecting refrigerant leakage is substantial.

Controls Faults

Short Cycling

Nominal efficiency of air conditioning is only reached after a few minutes of operation, due to thermal transients. Since most systems operate with “on-off” control, at partial loads the unit will naturally cycle between the “on” and “off” phases. If this cycling sequence is too short, however, the unit stops working before reaching an acceptable efficiency, with a great impact on energy consumption.

This problem can be caused by a bad thermostat setting or oversizing.

Economizer Malfunction

On average, 64 percent of the sample units presented some kind of economizer failure or tuning problem. These different faults were observed:

- Broken, frozen, or missing drive system components
- Outside air or mixed air sensor failure
- Faulty repairs
- Low changeover temperature setpoint
- Use of a single-stage cooling thermostat

The energy impact can be estimated between 14 and 40 percent, according to whether the economizer is malfunctioning or not functioning at all.

Thermostat Errors

- Improper thermostat (single-stage cooling only)
- Cycling fans during occupied periods
- Continuous fans during unoccupied periods
- Improperly installed resistors
- No nighttime setup or setback

Savings can vary. Correcting cycling fans during occupied periods will even increase the energy use (but improve indoor air quality). The highest savings, up to 40 percent, will occur when the thermostat is preventing the economizer from operating.

Failed Sensor

This problem has been noted in 20 percent of the units. The energy savings for repairing sensors vary over a wide range. They can be modest if the value is slightly incorrect, but can go up to 40 percent if they enable a non-functioning economizer.

CRITERIA FOR EVALUATING FDD APPROACHES

In order for an FDD approach to be viable in the market and to be justifiably included in Title 24, it must meet several criteria. The primary criteria for Title 24 are energy savings and cost-effectiveness. The primary criteria for the market are somewhat different, however. To be successfully marketed, the tool must be low-cost, marketable, and must reliably detect important problems in buildings. Of course, the role of codes is to get building owners to implement measures that the market for some reason or another is not successfully providing. This would suggest that even if a product does not meet marketability criteria, it can still be effectively implemented in Title 24, as long as it meets the criteria for code inclusion.

Ideally, this report would provide actual numerical metrics for these criteria. It should be noted, however, that most of the criteria are quite difficult to assess (particularly when discussing "hypothetical" tools). Diagnostic tools in general are difficult to assess because it is never known ahead of time how many and what type of faults will be detected. It is beyond the scope of this project to provide quantifiable metrics for each criterion. It should be possible, however, to compare different tools and describe characteristics somewhat qualitatively. When evaluating the different approaches, the project team used a scale of High, Moderate, or Low to describe whether the criteria are met Fully, Partially, or Not at all.

Magnitude of Energy Savings

The energy savings expected from an FDD approach depend entirely on the type and number of faults that can be detected and addressed. Reductions in greenhouse gas emissions go along with these energy savings.[2] Some of the faults that RTUs experience are listed below, along with an indication of the relative magnitude of energy savings possible through remedying the faults.

High Energy Savings

- Compressor valve leakage
- Condenser coil fouling
- Inadequate airflow
- Economizer malfunction
- Economizer misapplied
- Other controls problems

Moderate Energy Savings

- Refrigerant leakage/undercharge/overcharge
- Liquid line restriction

[2] Of course, HVAC refigerants currently in use are themselves notable sources of greenhouse gases, and the detection of leaks when they occur can contribute to a reduction in greenhouse gases.

Low Energy Savings

- Short-cycling

Cost-Effectiveness

The cost-effectiveness[3] of a diagnostic approach is dependent upon the potential savings, of course. But it is also dependent upon the cost to implement the method. The cost is based upon the type of data that is required, the overall number of points required, any processing capabilities that must be added, and communications hardware and access.

The principal cost incurred for FDD is for data collection. Depending on the method used, existing sensors installed in the RTU might be used. Care must be taken to ensure that the sensors are of sufficient accuracy and are installed in the appropriate location. In some cases, redundant sensors might be needed to take the place of the existing sensors. The relative cost-effectiveness of some typically used sensors is listed below:

High Cost-Effectiveness

- Fan on/off
- Compressor on/off
- Operating mode: Cooling/heating/ventilation
- Outdoor air damper position
- Current/kW

Moderate Cost-Effectiveness

- Suction temperature
- Liquid temperature
- kWh

Low Cost-Effectiveness

- Ambient temperature
- Return air temperature
- Supply air temperature
- Static pressure
- Suction pressure
- Liquid pressure

[3] Defined as the life-cycle Net Present Value of the incremental benefit of the technology (including the time-dependent value of reduced energy consumption, maintenance costs, and quatifiable non-energy benefits such as improved comfort), divided by the sum of the incremental first costs and Net Present Value of all other incremental costs associated with the technology (including maintenance costs and costs of remediation of faults).

- Discharge pressure
- Power factor
- Power quality

Processing of diagnostic algorithms can take place in the onboard controller, on an installed PC, or remotely. Even when a PC or remote computer is used, there may still be a need for on-site signal processing to reduce and pre-process the data. In most cases, these processing platforms do not contribute significantly to the cost. For some methods, however, cost impacts will be significant.

- High cost impacts: An approach that uses an energy management system (EMS) platform for processing
- Moderate cost impacts: An approach that can be accomplished by an embedded controller
- Low cost impacts: An approach that can be accomplished only with use of an added PC or processor

The defined scope for this program is remote diagnostics, so all approaches considered here will require remote communications. For remote diagnostics, communications hardware and access are required. This can be accomplished by tying into the building's EMS, or installing a dedicated modem and phone line. It is often possible to use a gateway to allow the diagnostic module to piggy-back on the building's communications infrastructure to reach the internet.

Frequency of Fault

A diagnostic tool is not as useful if it only detects faults that occur rarely. The more common the fault detected, the more appropriate it is for Title 24. The faults that are frequent in RTUs are described in Table 1 and are listed below, along with an assessment of their relative frequency.

High Frequency

- Inadequate airflow
- Refrigerant leakage/undercharge/overcharge
- Economizer malfunction
- Economizer misapplied

Moderate Frequency

- Condenser coil fouling
- Short-cycling
- Other controls problems
- Locked rotor
- Liquid line restriction

- Liquid slugging

Low Frequency

- Loss of phase
- Unbalanced voltage
- Compressor valve leakage
- Flooded start

Probability that Fault Will Get Fixed

It is easy to envision a code that requires manufacturers to install one of these types of FDD in factory units, or requires contractors to install "after-market" tools that will identify faults. However, it is somewhat more difficult to envision how these tools can be guaranteed to provide savings. After all, they merely note the fact that a fault exists; they do not fix it. Some method must be found to increase the probability that faults will be fixed.

Tools that diagnose problems that are likely to be fixed will be more likely to result in savings, so they are more likely to succeed in being implemented in code.

High Probability

- Refrigerant leakage/undercharge/overcharge
- Condenser coil fouling
- Inadequate airflow
- Liquid line restriction
- Other controls problems
- Locked rotor

Moderate Probability

- Liquid slugging
- Compressor valve leakage
- Economizer misapplied
- Economizer malfunction

Low Probability

- Loss of phase
- Unbalanced voltage
- Flooded start
- Short-cycling

Reliability, Robustness

Reliability and robustness in a FDD tool refers to a number of factors that influence whether a tool can be expected to work well over time. Some of these factors are:

- How difficult is it to install the tool? Installation errors, such as placing sensors in the wrong location or mounting them incorrectly, can render a FDD tool useless. How prone is the tool to mis-installation? Airside sensors can be difficult to install correctly, and care must be taken to mount them in the correct location so that they accurately reflect the temperature of an entire air-stream. Refrigerant sensors are somewhat less difficult to install, but they are also prone to mounting errors, as when temperature sensors are not mounted in direct enough contact with the lines being measured.

- Does the tool require maintenance? Some sensors, such as relative humidity (RH) sensors and pressure gauges, require periodic calibration. Any tool that requires such maintenance will be less robust than tools with maintenance-free sensors.

- A tool is only useful to a customer or technician if the tool's rates of false alarms and missed diagnoses are minimized. False alarms are a serious problem in FDD tools, and anything that generates unreliable alarms and causes alarm overload will not be used for long. Similarly, if a tool cannot be counted on to detect when a system is failing, it cannot be relied upon to provide remote diagnostics. This delicate balance must be found for every tool and every type of fault detected.

High Reliability

- No maintenance required
- No installation required
- False positives and negatives are both minimized

Moderate Reliability

- Minimal maintenance required
- Installation is easy to perform
- Moderate level of false positives and negatives

Low Reliability

- Significant maintenance required
- Installation prone to errors
- High false positives or negatives

Ease of Deployment

FDD tools can be deployed in many different ways. Three deployment models are described.

Performance Monitoring

Ongoing optimization of the use of the unit for a given environment can be referred to as performance monitoring. Many FDD tools can be deployed in this way.

Commissioning

Commissioning refers to a process of evaluating if a newly installed or existing unit is performing as expected. It is a one-time intervention where a technician is on-site, so it does not require remote access. FDD tools used in commissioning typically do not require historical data, although performance monitoring data can be used to supplement the commissioning tool. It is difficult to envision how commissioning tools would be included as a requirement in Title 24, unless commissioning interventions were also required.

There are already tools available that assist service providers in diagnosing a system in the context of a commissioning-like process. The Honeywell Service Assistant, provided to the market by various California utilities through their "Air Care Plus" programs, is one example. It is difficult to imagine the building code requiring an intervention such as this, although it could require enabling technology that would make these kinds of interventions possible. They would not generate savings on their own, however.

Maintenance

By optimizing maintenance operations, failures can be avoided and running costs can be optimized.

The match between these situations and the available FDD methods (described later in Definition of FDD Approaches) can be summed up as follows in Table 3:

Table 3: Assessment of Deployment Capability for Different Types of Models

Deployment Method	Quantitative	Qualitative	Timeseries
Performance Monitoring	High	Moderate	Moderate
Commissioning	High	Moderate	Low
Maintenance	High	High	High

Quantitative approaches seem to give the best performance but their use in the field seems unlikely due to the complexity and computational costs associated with them.

The other two types of approaches should be able to provide the required performance for the maintenance deployment but will provide very different results in term of commissioning and operation optimization.

Since the process timeseries method relies on previously logged data, it will not be able to detect any fault initially present in the system. This is quite a big limitation since much anecdotal evidence seems to show that errors are often introduced into the system during the installation of the units.

A qualitative model, on the other hand, does not rely on a baseline operating condition to evaluate the behavior of the system and could therefore diagnose errors at any time of the lifecycle of the unit.

The performance monitoring aspect, however, being linked to numerical values of efficiency criteria, cannot be included in a qualitative model, whereas a process timeseries-based model can definitely detect a variation of performances due to an operation optimization.

If neither commissioning nor operation behavior evaluation want to be left aside, some hybrid approach combining both methods could be envisioned.

Other Maintenance Benefits

While not valued in the cost-benefit analysis done for Title 24, most FDD tools also provide maintenance benefits to the customer, service contractor, or both. This is key to the marketability of FDD. The value of some of the maintenance benefits are:

High Maintenance Benefits

- Allowing contractors to send the right technicians with the right tools. By diagnosing problems remotely, the contractor can plan for a service call more accurately. This saves time and travel costs by avoiding second trips.
- Increasing uptime for customers, many of whom would suffer great financial losses if the RTU were to go down. A service that can avoid system failures would provide a great benefit to a customer and a great differentiator for a contractor, who could charge a premium rate for this advanced service.
- Ensuring that maintenance or service is done correctly, to avoid callbacks. Unbillable callbacks are a real drain on contractors' bottom lines. An example of this is systems that can ensure that charge has been adjusted correctly.

Moderate Maintenance Benefits

- Reducing the frequency of required maintenance by annunciating when maintenance is required. While this would seem to be a benefit to service contractors, those interviewed for this study indicated that they would not be likely to rely on this and would provide service calls on the usual schedule. They might reduce unscheduled maintenance, however.
- Allowing maintenance to be provided remotely. By assessing the condition of a system remotely, a service technician might be able to provide service to the customer over the phone, or even to make changes in controls remotely. This reduces unscheduled maintenance calls.

Low Maintenance Benefits

- Reducing the time required for a service call. A diagnostic tool that helped a service technician to do his or her job on the roof will have a benefit in reducing the time for a particular job. This is not as great a benefit as avoiding a service call, but if it allows for more jobs per day, it is a benefit.

DEFINITION OF FDD APPROACHES

With a good understanding of the criteria for selecting appropriate FDD tools, this report turns its focus to potential FDD solutions adapted to rooftop packaged air conditioning systems and heat pumps from 5 to 50 tons. All of the listed solutions may not be available on the market; the goal is to give the broadest possible view of the different approaches.

The objective of an FDD system is to detect faults early, diagnose their causes, and enable correction of the faults before additional damage to the system or loss of service occurs. This is accomplished by continuously monitoring the operating conditions and comparing them to a model of expected performance. When actual measured operation does not match expectations determined with use of a model, a fault is detected. Ultimately, the objective is to ensure that the building owner or operator will respond in an appropriate manner, remedying the problem.

This report defines a method of classifying different approaches to FDD, and evaluates their potential for use in the market or in Title 24 Building Standards.

Classification of FDD Tools

There are two ways of characterizing FDD tools: one is based on the set of measured data points the tool uses to perform its analysis, and the other is to look at what sort of model is used to determine expected performance. Each of these factors has a strong influence on the final capabilities of the system.

Classification Based on Input Data

The input data acquired naturally falls into three distinct groups: airside data, refrigerant cycle data, and power data.

Airside

- Outdoor-air dry-bulb temperature
- Return-air dry-bulb temperature
- Mixed-air dry-bulb temperature
- Outdoor air damper-position signal
- Supply-fan status
- Heating/cooling mode
- Outdoor air relative humidity (for enthalpy-based economizers)
- Return air relative humidity (for differential enthalpy controls)

Refrigeration Cycle

- Suction pressure
- Liquid pressure

- Discharge pressure
- Suction temperature
- Liquid temperature
- Ambient temperature
- Return air temperature
- Supply air temperature

Some methods substitute the pressure monitoring with additional temperature sensors (Breuker and Braun 1998b).

Power Monitoring

- Fan, compressor, or RTU kW
- kWh
- Power factor
- Real and reactive power
- Power quality

Classification Based on FDD Model

The different approaches can also be characterized by the models used to determine expected performance. For example, for a first principle-based or engineering model, physical laws are used to predict the behavior of the system. On the other end of the spectrum, black box models rely only on data from the process itself, and the resulting model may not have any physical significance. Table 4 (see following page) illustrates some of the pros and cons of the different methods.

Quantitative Models

Quantitative models are directly based on the physics of the process under consideration. According to the degree of complexity, they can either be steady state, linear dynamic, or non-linear dynamic. In this case, for a given set of measured inputs (temperature, pressure, etc.), it is possible to calculate the expected behavior and compare it to the measured performances of the system (analytical redundancy). The differences (residuals) can then be evaluated to detect any fault within the system.

Qualitative Models

Qualitative models can be based on a set of rules (inferred from the physics or expert knowledge) or on qualitative physics instead of relying on quantitative mathematical relationships. Since measurement techniques usually provide quantitative inputs (temperature, etc.), some pre-processing is often required to convert this information into qualitative inputs. One of the methods that can be used, for example, is fuzzy logic and other kinds of classifiers.

In the case of a rule-based modeling technique, a set of if-then-else rules are derived from *a priori* knowledge.

In expert systems, the rules are derived from insight, knowledge, or guidance from people with expertise in the field. Another method is to derive the rules from a first principle approach, implemented in a tree structure within the software. Data gathered during the system operation allows navigating the decision tree and reaching a conclusion about the unit's behavior.

This approach is entirely data driven: a known set of input and output data is fed to the system, which then tries to find a mathematical relation between the data. This is called parameter extraction. Two different approaches coexist; if these parameters have no physical meaning, the approach is qualified as "black box." If the choice of parameters is based on a first principle approach and their value is obtained through linear regression from the set of data, we speak about a "grey box" approach instead.

Various methods exist for both approaches. The main difference between the two lies in their abilities to make predictions outside of the training data range.

FDD Approach Matrix

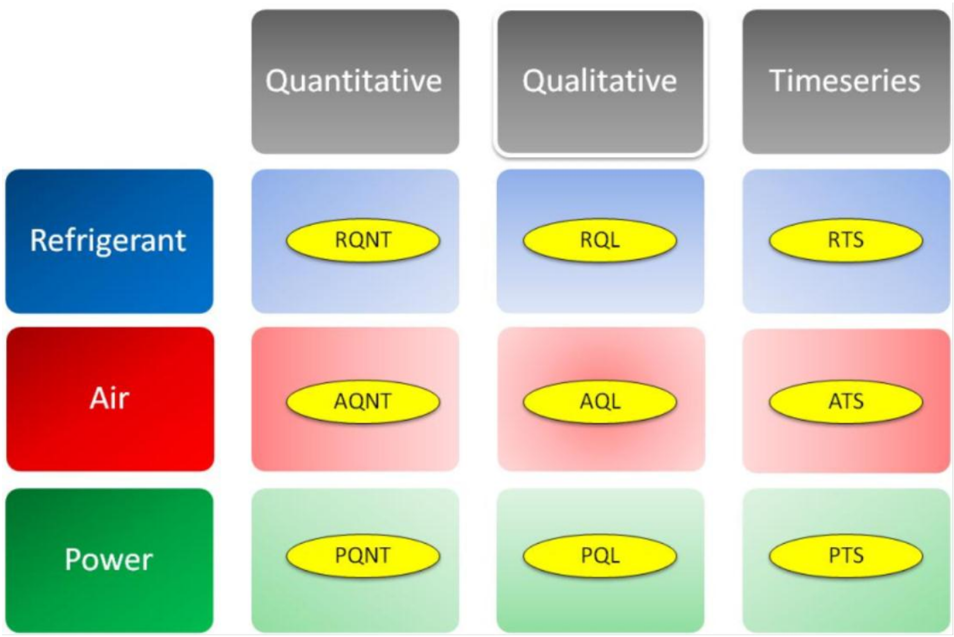
This report has defined two ways of categorizing FDD systems: 1. by the type of data required and 2. by the type of model used. When this information is combined, an FDD Approach Matrix can be defined in which almost any possible FDD approach can be located, as shown in Figure 1.

Table 4: Strengths and Weaknesses of FDD Models

Type of Model	Strengths	Weaknesses	Suitability for FDD
Quantitative Models	• Based on sound physics • Most accurate estimators of outputs, if well-formulated • Detailed models can also simulate faulty operation for easier detection • Allow the modeling of transients	• Complex and computationally intensive • Significant development effort • Many required inputs; some not readily available • Sensitivity to poor user inputs	• Detailed models unlikely to be a solution of choice • Simplified models may be used
Qualitative Models	• Well-suited for data-rich environments • Simple to develop and apply	• Specific to a system or process • Difficult to find a complete, applicable set of rules, mostly	• May prove a good choice if quantitiative approaches too demanding • Good for one-time

Type of Model	Strengths	Weaknesses	Suitability for FDD
	• Transparent reasoning; works under uncertainities • Ability to provide explanations for diagnostics because relies on cause-effect relationships • Some methods do not require special knowledge of the system and accurate data	for complex systems • Simplicity can be lost as new rules are introduced • Depends on the expertise of the developer	assessments
Process Timeseries-Based Models	• Well-suited if theoretical models are unavailable /inaccurate • Well-suited if training data is abundant/ cheap • No previous understanding of the system physics required for black box models • Usually low computational requirements • Theoretical foundations widely documented	• Gray box models require a good process knowledge and statistic expertise • Low performances outside of the training data range • Large amount of data for all expected operation models required • Models are specific to a system • Takes time to collect a training dataset • Requires a training set representing correct operation	• Suitable where no other methods exists • Lower cost than some methods • Good for long-term assessments

Figure 1: FDD Approach Matrix, Used to Classify FDD Approaches



Each cell in this matrix will be studied in detail. Most cells do not represent available tools, but one can still envision what the characteristics of tools would be in these cells. The sections that follow describe these "hypothetical" approaches in detail. Where there are actual tools available, they will be cited as examples and described. By evaluating hypothetical approaches, we can identify which would have the potential for appropriate tools and for Title 24. This will simplify the search for appropriate tools by allowing us to focus on a smaller set of tools.

DESCRIPTION OF AVAILABLE AND DEVELOPING TOOLS

There are very few tools currently on the market. A handful of tools have been piloted but have not yet been introduced to the market as viable products, and yet others are under development. While this report discusses the approaches that can be taken to FDD in a generic "hypothetical" way, it is useful to describe the tools that are commercially available, available in pilot status only, or in the pipeline. Tables 5 through 7 describe the types of FDDs, the faults detected by each, and the required input data, respectively. Information is shown for "Basic" diagnostics (that implemented in the standard version of each tool) and "Extended" diagnostics (that implemented in potential extended versions). Each of these tools is further described later in the report.

Table 5: Available Tools

Tool Name	Data	Model	Status	Developer
FDSI Insight V.1	Refrigerant	Quantitative	Available	Field Diagnostics, Inc.
Sentinel/Insight	Refrigerant	Quantitative	Beta	Field Diagnostics, Inc.
ClimaCheck	Refrigerant	Quantitative	Available	ClimaCheck Inc.
SMDS	Air	Qualitative	Pilot	Pacific Northwest National Laboratory
Sensus MI	Air	Qualitative	Available	University of Nebraska
NILM	Power	Qualitative	Pilot	Massachusetts Institute of Technology
Low Cost NILM	Power	Timeseries	Pilot	Massachusetts Institute of Technology
Virtjoule	Power	Timeseries	Developing	Virtjoule Inc.
Low Cost SMDS	Air-Power	Timeseries	Developing	Pacific Northwest National Laboratory

Table 6: Faults Detected by Available Tools

O	Basic FDD
X	Extended FDD

	FDSI Insight V.1 Production	Sensus MI	ClimaCheck	SMDS	NILM	Low Cost NILM	Sentinel/Insight Beta Testing	Virtjoule	Low Cost SMDS
Low Airflow	O	O	O		O	O	O	O	
Low/High Charge		O	O		O	O	O	O	
Sensor Malfunction	O	X	O	O			O	X	
Economizer not Functioning	O	X	X	O			O	O	
Compressor Short Cycling	O	X	O		O	O	O	O	O
Excessive Operating Hours	O	X	O				O	O	O
Performance Degradation		O	O	O	O	O	O	O	O
Insufficient Capacity	O	X	O				O	X	O
Incorrect Control Sequence	O	X	O		O	O	O	O	
Lack of Ventilation	O	X		O			O	X	
Unnecessary Outdoor Air	O	X	X	O			O	X	
Control Problems	O	X	O	O			O	O	
Failed Compressor	O	O	O	O	O	O	O	O	
Stuck Damper	O	O	O	O			O	X	
Slipping Belt	O	O	O		O		O	O	
Leaking Valves			O		O		O	X	
Unit Not Operational	O	X		O	O	O	O	O	O

Table 6: Faults Detected by Available Tools

O	Basic FDD
X	Extended FDD

	FDSI Insight V.1 Production	Sentinel/Insight Beta Testing	ClimaCheck	SMDS	Sensus MI	NILM	Low Cost NILM	Virtjoule	Low Cost SMDS
Suction Pressure		O	O		X				
Discharge Pressure			O		X	O			
Suction Temperature		O	O		X				
Discharge Temperature		O	O		X				
Liquid Temperature		O	O		X				
OAT	O	O	O	O	O				O
RAT	O	O	O	O	O				O
MAT				O	O				O
SAT	O	O	O	O	O			X	
Condenser leaving air temp			O						
OARH					X				
RARH	O	O			X	O			
MARH				O	X				
SARH				O	X			X	
Damper Position			X	O				X	
Operating Mode	O	O	X	O	O				
Compressor Status			X	O	O				
Fan Status			X	O	O				
Vibration								O	
Fan, Compressor, or RTU kWh			O	O					O
Power factor						O			
Real/reactive power			O			O			
Power Quality						O			
Compressor Voltage									
Compressor Amperage									
RTU Voltage						O	O	O	
RTU Amperage	O	O				O	O	O	

DESCRIPTION OF POTENTIAL FDD APPROACHES

For each cell in Figure 1, this report describes the following aspects of the hypothetical, available, and developing tools:

- Required information: What information set does the system need to access? Some of this information is readily available from standard/higher-end RTU control boards, whereas other information is obtained via additional sensors.
- Example of detected faults: This list of faults is based on publications detailing the operation of this FDD solution (if available) or on engineering knowledge. This is by no means exhaustive but serves as an illustration of the potentialities of the system.
- Hardware requirements: Based on the required information and the type of processing envisioned, it is possible to list the necessary components and an approximate price, if available.

Refrigerant Quantitative Model Approach

This approach works by comparing performance indices calculated by an internal model on one side, and obtained by processing input values on the other side. By observing the residuals, it is possible to detect faults in the system.

Required Information

- Suction pressure*
- Liquid pressure*
- Discharge pressure*
- Suction temperature
- Liquid temperature
- Ambient temperature
- Return air temperature
- Supply air temperature

*can be substituted with additional temperature sensors

Based on that information, the system can evaluate performance indices such as:

- Evaporation temperature
- Superheat
- Condenser temperature
- Sub cooling

- Evaporator Delta T
- Condenser over ambient

Example of Detected Faults

- Faulty refrigerant charge
- Compressor valve leakage
- Liquid line restriction
- Condenser fouling
- Inadequate airflow

Hardware Requirements and Pricing Elements

- Temperature/pressure sensors
- Data processing module in order to run the physical model
- Communication module (required for any FDD)

Example Available Tool: Sentinel and Insight

The Sentinel provided by Field Diagnostic Systems is an example of a refrigerant-side tool that uses quantitative methods to diagnose system condition. Due to the high cost of the Sentinel, with its requirement for a number of sensors to be installed, FDSI has developed the Insight analysis tool, which makes use of onboard sensors and data acquisition systems to provide the same diagnostics.

Example Available Tool: ClimaCheck

Description

This system, developed in Sweden, allows the continuous monitoring of refrigerant systems. Available either in portable or fixed installation format, the system is composed of the following elements:

- Data acquisition system (PA Pro)
- Power meter
- Temperature sensors
- Pressure sensors
- ClimaCheck software
- Optional local area network (LAN) connection or General Packet Radio Service (GPRS) modem

The system is based on an internal thermo-physical model and can therefore be used on any kind of refrigerant system. It allows the user to assess system performance based on temperature, pressure, and power measurements.

Because of its cost, this tool is applied most frequently as a service productivity tool, rather than an ongoing degradation detector. It is typically used in a service offering in which an experienced technician uses the tool to efficiently assess the condition of one or more RTUs at a facility.

An evaluation of possible savings, documented in “Energy Optimisation Potential through Improved Onsite Analysing Methods in Refrigeration” (Arul Mike Prakash 2006), found that out of 49 analyzed air conditioning systems, 44 had faults. The most frequent faults detected were related to charge (70 percent of units), expansion valves (30 percent) and secondary flow (11 percent). No values on efficiency are documented, but an average variation in COP of -11.5 percent was documented.

<u>Cost</u>
A complete unit costs approximately $5,000-$6,000.

Refrigerant Qualitiative Model Approach

This approach is very similar to the previously described “refrigerant quantitative”approach, as in both cases a set of performance indices is calculated. In this case, however, the value of these indices is compared to tabulated target values, and the difference observed for each of these indices is used in a rule-based approach in order to identify the fault.

Required Information

- Suction pressure*
- Liquid pressure*
- Discharge pressure*
- Suction temperature
- Liquid temperature
- Ambient temperature
- Return air temperature
- Supply air temperature

*can be substituted with additional temperature sensors

Based on that information, the system can evaluate performance indices such as:

- Evaporation temperature
- Superheat
- Condenser temperature
- Sub cooling
- Evaporator Delta T

- Condenser over ambient

Example of Detected Faults

- Faulty refrigerant charge
- Compressor valve leakage
- Liquid line restriction
- Condenser fouling
- Inadequate airflow

Hardware Requirements and Pricing Elements

- Temperature/pressure sensors
- Data processing module
- Communication module (required for any FDD)

Refrigerant Timeseries Approach

In this case, no target for the performance indices is defined. The target values are obtained from the acquisition taking place during the first phase of operation.

Required Information

- Suction pressure*
- Liquid pressure
- Discharge pressure
- Suction temperature
- Liquid temperature
- Ambient temperature
- Return air temperature
- Supply air temperature

*can be substituted with additional temperature sensors

Example of Detected Faults

- Capacity to detect the following faults:
- Refrigerant leakage
- Compressor valve leakage
- Liquid line (LL) restriction
- Condenser fouling

- Inadequate airflow

Hardware Requirements and Pricing Elements

- Necessary addition of pressure sensors and/or additional temperature sensors => material and installation costs
- Data logger+ Simple signal processing (hardware for timeseries-based approach)
- Communication module (required for any FDD)

Air Quantitative Model Approach

By simulating the behavior of the unit for the measured input conditions and comparing the calculated and measured supply air temperature, it is possible to detect faults within the system.

Required Information

- Outdoor air temperature (OAT)
- Return air temperature (RAT)
- Mixed air temperature (MAT)
- Supply air temperature (SAT)
- Fan status
- Cooling/heating mode operation
- Outdoor air damper position

Example of Detected Faults

- Supply air temperature too high: inadequate airflow
- Supply air temperature too low: incorrect refrigerant charge/compressor leakage

Hardware Requirements and Pricing Elements

- Temperature sensors
- Data processing module in order to run the physical model
- Communication module (required for any FDD)

Air Qualitative Model Approach

This approach would get rid of the physical model of the quantitative approach, and rely on the variation of parameters and predefined acceptable ranges for each parameter to detect a faulty operation. This would be much simpler but would only be practicable during steady state operation.

Required Information

- Outdoor air temperature
- Return air temperature
- Mixed air temperature
- Supply air temperature
- Fan status
- Cooling/heating mode operation
- Outdoor air damper position

Example of Detected Faults

- Incorrect economizer setpoint
- Supply air temperature too high: inadequate airflow
- Supply air temperature too low: incorrect refrigerant charge/compressor leakage.

Hardware Requirements and Pricing Elements

- Temperature sensor
- Data processing module
- Communication module (required for any FDD)

Example Available Tool: Smart Monitoring and Diagnostics Systems

Description

Battelle Pacific Northwest Division in collaboration with NorthWrite Inc. has developed a tool for continuously monitoring the condition and performance of packaged air conditioners and heat pumps.

The Smart Monitoring and Diagnostic System (SMDS) is mounted in a small box installed on the side of each packaged air conditioner or heat pump and provides continuous remote monitoring and diagnostics for the unit. It requires the following components:

- Temperature sensor
- Data processing module
- Communication module (required for any FDD)

The SMDS works by constantly collecting data from sensors installed on the equipment to measure its performance and detect and to diagnose problems with its operation. The unit then sends the results wirelessly, directly from each packaged unit to a network operations center, where the data are stored securely and information on the condition of each packaged unit is made available on the internet. The SMDS can be installed on new or existing packaged air conditioners and heat pumps.

This approach gets rid of the physical model of the quantitative approach, and relies on the variation of parameters and predefined acceptable ranges for each parameter to detect a faulty operation. This would be much simpler but is only possible during steady state operation.

Cost
Approximately $2,000/unit + $200 to $1,000 for installation.

Other

The diagnostics provided in some high-end RTUs are an example of qualitative models that make use of airside data. For example, the Carrier controller can provide an alarm if a filter is clogged and if an economizer is malfunctioning, based upon various sensor readings, and a qualitative model of variables such as high static pressures and no damper movement mean. The tables that follow provide the alarm codes that may be useful for energy management for four high-end RTUs:

Table 8: Lennox Alarm Codes

Alarm	Problem	Action
6	S27 (Dirty Filter Switch) This indicates a dirty filter.	None.
59	Gas valve 1 not energized 3 (default) times (2 minutes after a demand). Check gas supply, ignition control and wiring. ECTO 3.09. (GV1)	Only action taken is storing code in memory.
75	Outdoor Temperature (RT17) Sensor Problem. Check wiring and sensor.	The control defaults to a high outdoor temperature operation.
91	Outdoor enthalpy sensor (A7) open. Check sensor and wiring.	No economizer free cooling operation if economizer mode is set to ODE or DIF.
92	Indoor enthalpy sensor (A62) open. Check sensor and wiring.	No economizer free cooling operation if economizer mode is set to DIF.
93	The control has changed the system mode because of an error with the controlling sensor or because of a loss of communication.	IMC has switched over to the backup mode option set with ECTO 6.01.
99	Outdoor Air Control Sensor (A24) open. Cleared by IMC reset.	No OAC operation. Damper closed to minimum position.

Table 9: York Alarm Codes

[Table text should be checked for clarity:]

Alarm	Problem
Alarm 13	Indicates the Space Temperature Sensor has failed open or shorted.
Alarm 14	Indicates the Supply Air Temperature Sensor has failed open or shorted.
Alarm 15	Indicates the Return Air Temperature Sensor has failed open or shorted.
Alarm 16	Indicates the Outside Air Temperature Sensor has failed open or shorted.
Alarm 17	Indicates the Dirty Filter Switch has tripped.
Alarm 1A	Indicates a microelectronics failure and the control is operating on defaults.
Alarm 1D	Indicates the Outside Humidity Sensor is out of range.
Alarm 1E	Indicates the Return Air Humidity Sensor is out of range.
Alarm 1F	Indicates the IAQ Sensor is out of range.
Alarm 25	Indicates the unit is locked out due to either 1) high duct static pressure, or 2) a faulty duct static pressure sensor with an output that is too high.
Alarm 26	Indicates the control has detected a Supply Air Temperature fault for Cooling.
Alarm 27	Indicates the control has detected a Supply Air Temperature fault for Heating.
Alarm 28	Indicates the control has detected a Minimum Economizer Position fault condition.
Alarm 29	Indicates the control has detected a Space Temperature Alarm condition.
Alarm 2A	Indicates a fault with the Duct Static Pressure sensor reading a low pressure when there should be pressure present.
Alarm 2B	Indicates the Hot Water Freeze Stat has opened, indicating a fault that could cause the coil to freeze.

Table 10: Carrier Alarm Codes

Alarm	Description	Probable Cause
T110	Circuit A Loss of Charge	Low refrigerant or faulty suction pressure transducer
T126	Circuit A High Refrigerant Pressure	An overcharged system, high outdoor ambient temperature coupled with dirty outdoor coil, plugged filter drier, or a faulty high-pressure switch
T133	Circuit A Low Refrigerant Pressure	Low refrigerant charge, dirty filters, evaporator fan turning backwards, loose or broken fan belt, plugged filter drier, faulty transducer, excessively cold return air, or stuck open economizer when the ambient temperature is low.
T408	Dirty Filter	Dirty Filter
T414	Economizer Damper Actuator Out of Calibration	Calibrate economizer (E.CAL). If problem still exists then determine what is limiting economizer rotation.
	Economizer Damper Actuator Torque Above Load Limit Alert	Actuator load too high. Check damper load.
	Economizer Damper Actuator Hunting Excessively	Damper position changing too quickly.
	Economizer Damper Stuck or Jammed	No economizer motion. Check damper blades, gears,and actuator.
	Economizer Damper Actuator Mechanical Failure	Check actuator and replace if necessary.
	Economizer Damper Actuator Direction Switch Wrong	Actuator direction control switch (CCW, CW) wrong.

Table 11: Trane Intellipak Alarm Codes

Alarm
Blocked Air Return
Energy Recovery Wheel Proof Failure
Improper Airflow for Dehumid
Low Pressure Control Open - Ckt 1
Low Pressure Control Open - Ckt 2
Low Refrigerant Charge - Ckt 1
Low Refrigerant Charge - Ckt 2
Cond Sump Min Level or Drain Failure
CO2 Sensor Failure
Min OA Flow SETPOINT Failure
Min Position SETPOINT Failure
OA Temp Sensor Failure
Return Air Temp Sensor Failure
Supply Air Temp Sensor Failure

Table 12: Trane Intellipak Alarm Codes Explained

DIAGNOSTIC DISPLAYED	REASON FOR DIAGNOSTIC	UCM'S REACTION	RESET REQUIRED
Low Refrigerant Charge (Ckt1 and/or Ckt2) Problem: The difference between entering and leaving evaporator temperatures is greater then Evaporator Temperature Differential SETPOINT for 10 minutes. Check: Status of refrigerant charge and running pressures on affected circuit.	Low refrigerant Charge (Ckt1 and/or Ckt2). The cooling circuit has been active for 10 minutes and the difference in the entering and leaving evaporator temperatures is greater than the Evaporator Temperature Differential SETPOINT for 10 continuous minutes.	A "Lockout (Ckt1 and/or Ckt2)" request is issued to the compressor Staging Control Function.	PMR) A manual reset is required anytime after the Diagnostic is set. The Diagnostic can be reset by the Human Interface or Tracer, or by cycling power to the RTM.
DIAGNOSTIC DISPLAYED	**REASON FOR DIAGNOSTIC**	**UCM'S REACTION**	**RESET REQUIRED**
Minimum Outdoor Air Flow SETPOINT Failure Problem: The input designated as the SETPOINT is out of range. Check: Wiring to the GBAS input designated for Minimum Outdoor Air Flow SETPOINT or check BAS/Network interface card status and wiring.	Minimum Outdoor Air Flow SETPOINT out of range: OA flow is < 0 or > Max Unit Airflow (46000 CFM for 90 and 105 Ton and 58500 CFM for 120 Ton and up).	The active Minimum OA Flow SETPOINT reverts to the default Minimum OA Flow SETPOINT.	(PAR) An automatic reset occurs after the Minimum OA Flow SETPOINT input returns to within range for 10 continuous seconds, or after a different, valid Minimum OA Flow SETPOINT selection source is user-defined.
Supply Air Temperature Sensor Failure Problem: The Supply Air Temperature sensor input is out of range. Check: Sensor resistance should be between 830 ohms (200 F) and 345.7Kohms (-40 F). Check field/unit wiring between Sensor and RTM.	The unit is reading a signal that is out of range for the Supply Air Temperature input on the RTM (Temperature < -55 F or Temperature > 209 F).	These unit functions are disabled; a. Supply Air Tempering b. Economizing c. On CV units, the Supply Air Temperature low limit function is disabled. d. On VAV units, the Supply Air Temperature Control heating and cooling functions are disabled.	(PAR) An automatic reset occurs after the designated Supply Air Temperature input returns to its allowable range. In order to prevent rapid cycling of the Diagnostic, there is a 10 second delay before the automatic reset.
Return Air Temperature Sensor Failure Problem: On units with the Comparative Enthalpy option, the Return Air Temperature sensor input is out of range. Check: Sensor resistance should be between 830 ohms (200 F) and 345.7Kohms (-40 F). If so, check field/unit wiring between Sensor and ECEM.	The unit is reading a signal that is out of range for the Return Air humidity sensor (Temperature < -55 F or Temperature > 209 F).	The Economizer Enable r.e. Enthalpy function reverts to Reference Enthalpy changeover ("Level 2") control.	(PAR) An automatic reset occurs after the RA Temperature input returns to its allowable range continuously for 10 seconds.
OA Temperature Sensor Failure Problem: The Outside Air Temperature sensor input is out of range. Check: Sensor resistance should be between 830 ohms (200 F) and 345.7Kohms (-40 F). If so, check field/unit wiring between Sensor and RTM.	The unit is reading a signal that is out of range for the Outside Air Temperature sensor input on the RTM. (Temp < -55 F or Temp > 209 F).	Unit functions that are disabled include; a. Low Ambient Compressor Lockout b. The Outside Air Damper drivestominimumposition. c. On VAV units with SA Temp Reset type selected as OA Temp Reset, the Reset type reverts to NONE for the duration of the failure.	(PAR) An automatic reset occurs after the OA Temp input returns to its allowable range. In order to prevent rapid cycling of the Diagnostic, there is a 10 second delay before the automatic reset.

Air Timeseries–Based Model Approach

In this case, there is no need for a physical model, and no maps, thresholds, or set of rules have to be defined: the system logs the system state for different input conditions and defines patterns. If at some point during the system life the behavior of the system does not match these patterns, the system is considered faulty.

- Outdoor air temperature
- Return air temperature
- Mixed air temperature
- Fan status
- Cooling/heating mode operation
- Outdoor air damper position

Example of Detected Faults

- Economizer errors or thermostat setpoint errors can be detected by comparing the mode of operation (cooling/heating, fan on/off, damper position) for similar OAT/RAT/MAT and schedule.
- Capacity degradation can be seen from a variation in compressor cycling for similar OAT/RAT temperatures.
- Fouled filter or other airway obstructions can be detected by an increased mixed air temperature for a given mode of operation and return/outdoor air temperatures.

Hardware Requirements and Pricing Elements

- Factory sensors/information => no additional sensor required
- Data logger+ Simple signal processing (hardware for process timeseries-based approach)
- Communication module (required for any FDD)

Example Available Tools: Sensus ML

Description
This product is entirely software-based and leverages on the information already available through the Building Automation System (BAS) system.

Cost
The cost is very low due to low capital and installation costs: return on investment (ROI) < 1 year.

This approach necessitates running a complete model taking into account the fluid dynamics, mechanical, and electromechanical aspects of the system in order to calculate the instantaneous power and required power requested by the unit. The level of complexity involved renders this approach impracticable.

Power Quantitative Model Approach

In this case, the requested power profile of the unit is compared with target values stored into the controller for the different phases of the system.

Required Information

Current and voltage sensors at the RTU feed. In case of a three-phase system, two of each is necessary.

Example of Detected Faults

Electrical/electromechanical RTU faults:

Fault	Diagnostic Method
Loss of phase	Current and voltage
Locked rotor	Start transient
Slow-starting motor	Start transient
Unbalanced voltage	Voltage
Short-cycling	Event sequence
Motor disconnect/failure to start	Event sequence
Incorrect control sequence	Event sequence
Contactor (improper contact closure)	Phase current interruption transient
Fan rotor faults that result in imbalance	Amplitude spectrum in steady operation

Non-electrical RTU faults:

Fault	Diagnostic Method
Refrigerant leakage, undercharge, or overcharge	Change of mean
Loss of volumetric efficiency (leaky valves, seals)	Start transient
Fouled condenser coil	Change of mean
Dirty supply air filter	Change of mean
Liquid ingestion *1	Anomalous transient
COP degradation *2	

*1 requires refrigerant flow (or compressor map) and head pressure
*2 requires airside flow and RH

Hardware Requirements and Pricing Elements

- Single-phase diagnostic can be implemented in a low-cost 150 MHz PC-on-a-chip with a two-channel A/D converter, with an incremental RTU manufacturing cost as low as $200.
- Communication module (required for any FDD)

Air Qualitative Model Approach

Source: Armstrong et al. 2004 2006

This approach is based on Non-Intrusive Load Monitoring (NILM), which is the measurement of power and reactive power used by the unit.

In this case, many faults are diagnosed by looking at transients, which implies a relatively high sampling frequency of around 120 Hz.

This method differs from the qualitative power approach since the target values are not entered as system parameters but are obtained from the first phase of operation.

Required Information

Current and voltage at the RTU feed. In the case of a three-phase system, two of each is necessary.

Example of Detected Faults

Electrical/electromechanical RTU faults:

Fault	Diagnostic Method
Loss of phase	Current and voltage
Locked rotor	Start transient
Slow-starting motor	Start transient
Unbalanced voltage	Voltage
Short-cycling	Event sequence
Motor disconnect/failure to start	Event sequence
Incorrect control sequence	Event sequence
Contactor (improper contact closure)	Phase current interruption transient
Fan rotor faults that result in imbalance	Amplitude spectrum in steady operation

Non-electrical RTU faults:

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Fouled condenser coil	Change of mean
Dirty supply air filter	Change of mean
Liquid ingestion *1	Anomalous transient
COP degradation *2	

*1 requires refrigerant flow (or compressor map) and head pressure
*2 requires airside flow and RH

Hardware Requirements and Pricing Elements

- Single-phase diagnostic can be implemented in a low-cost 150 MHz PC-on-a-chip with a two channel A/D converter, with an incremental RTU manufacturing cost as low as $200.
- Communication module (required for any FDD)

Example Available Tool: Virtjoule

Description
This system would be composed of RTU power sensors, communicating with the Virtjoule gateway using ZigBee protocol. This allows the information to be shared with the Virtjoule network operation center (NOC). Data is then processed and communicated to the end-user via different possible channels (web-service, email, short message service [SMS], etc).

Approach
The basis for the analysis is the usage metering and power signature provided by the power sensor. This raw information, routed to the NOC, is then combined with additional data such as historic data or local weather information in order to detect and classify faults.

Cost
Typical ROI < 1.5yr

Example Available Tool: Non-Intrusive Load Monitoring (NILM)

The NILM device, developed by the Massachusetts Institute of Technology, is an example of a power-monitoring tool that uses timeseries-based methods to diagnose system conditions.

This approach was first developed to investigate the energy use in whole buildings. It has been dubbed non-intrusive because the hardware can be connected to the electric power supply to the building, so that end-use meters do not need to be connected to every appliance.

The only required sensors are current and voltage sensors on the system.

In looking at instantaneous real and reactive power, and knowing that each load has its own resistance, inductance, and capacitance characteristics, it becomes possible to single out each individual load.

In the case of packaged air conditioning units, the loads are limited to the compressors and fans. It is therefore easy to detect which component is running. If this information is combined with one or two air temperature measurements, it becomes possible to get an insight into the working conditions of the system, and changes in efficiency or major fault occurrences can be detected. By combining information about the power uses with outdoor air and return air temperatures, changes in energy efficiency and occurrence of major faults can be detected.

Hybrid Power/Airside Timeseries-Based Model Approach

This approach focuses on reducing the cost of the device, and therefore focuses on faults that can be diagnosed by looking at event sequences. In this case, the system can be very simple since there is no need to measure the reactive power, and the sampling frequency can be also reduced (target: a few samples/minute).

This approach is called "hybrid" because it also requires some temperature information from the air side methods.

This approach is very close to the air side timeseries-based model in terms of both required information and the way this information is treated. The main difference is that information about the state of the fans and compressor is obtained from the power measured at the RTU feed.

Required Information

- Power-meter
- OAT/TAT/MAT temperatures

Example of Detected Faults

- Efficiency degradation by increases in the total power use given the outdoor air temperature
- Degradation in capacity from:
  - Increase in "on" time per cycle for each specific outdoor air temperature
  - Continuous operation without cycling at a lower outdoor air temperature or lower outdoor air enthalpy than previously observed
- Operation during unoccupied times (or incorrect schedule specification) via power level indicating supply fan, condenser fan, and compressor are operating during times when the building or specific building zones are not occupied

- Excessive cycling indicated by compressor power cycling at a frequency higher than acceptable
- Unit not operational - zero power during conditions (e.g., time of week and outdoor air temperature) when the unit has historically operated

Hardware Requirements and Pricing Elements

Power meter: the small number of electric components in a typical RTU (two to four) makes the identification of the running components straightforward, obviating the need to measure the reactive power. The requested temperature sensors are usually already available. The remaining hardware includes a transmitter, the cost of which may vary according to the technology used. Target price: $100-$400

Example Available Tool: Lo-Cost SMDS

The Low-Cost Diagnostic Module proposed by Pacific Northwest National Laboratory is an example of a power monitoring tool that uses qualitative methods to diagnose system condition from power monitoring and simple airside measurements.

EVALUATION OF APPROACHES

The sections that follow describe how well the different FDD approaches meet the criteria just discussed, and Table 13 below provides a summary of this assessment. Recall that only a qualitative assessment of most of the criteria can be provided, so a scale has been used to describe whether each of the criteria are met fully, partially, or not at all.

Table 13: Summary of Evaluation of Different Fault Detection Approaches

●=High ◌=Moderate ◌=Low

	Savings	Cost Eff	Frequency	Fixed	Reliable	Deployable	Maint.
Refrigerant-side Quantitative	●	◌	●	●	◌	●	●
Refrigerant-side Quantitative	●	◌	●	●	◌	●	●
Refrigerant-side Timeseries	●	◌	●	●	◌	◌	●
Airside Quantitative	◌	◌	●	◌	◌	●	●
Airside Qualitative	●	◌	●	●	●	●	●
Airside Timeseries	●	◌	●	●	●	◌	●
Power Quantitative	●	●	●	●	●	●	●
Power Timeseries	●	◌	●	●	●	◌	●
Hybrid Airside/Power Timeseries	●	●	●	●	●	◌	◌

MAGNITUDE OF ENERGY SAVINGS

All approaches can offer significant energy savings. The Airside Quantitative approach provides somewhat lesser savings, because there are a limited number of situations it can diagnose. Most tools can identify refrigerant charge and airflow issues, which may have the potential for energy savings. Several approaches can identify economizer problems, and only one aprroach (Hybrid Air/Power Timeseries-Based) specializes in issues such as nighttime operation. Depending on the cost, it is likely that any of these methods would provide moderate or high energy savings, and would be suitable for inclusion in Title 24. The energy savings may not be dependable enough to drive marketability, however.

Cost-Effectiveness

The Power Qualitative and Hybrid Air/Power Timeseries-Based models would seem to have the most potential to be cost-effective. Since they require a very minimal set of data, the cost of acquiring data would be quite small. If they require significant hardware for processing, however, the costs will rise. Most of the rest of the approaches would provide moderate levels of cost-effectiveness but would have to be analyzed carefully to determine whether or not they were cost-effective. The refrigerant-based models, because of their requirement for a large number of sensors, can be expected to be less cost-effective. If these data can be obtained inexpensively (for example, through mass production and installation in the factory, or through the reliable use of existing sensors, as is done by FDSI's Insight and Sensus MI), then these methods may have some promise.

Frequency of Fault

All of the approaches address faults that have a significant frequency of occurrence. As described earlier, most existing RTUs can be expected to have one of the problems that each of these approaches can detect.

Probability Fault Will Get Fixed

Because most of the methods can detect issues such as incorrect refrigerant charge and the need for filter replacement, it is likely that the faults will be remedied once detected. Those faults are not necessarily the most important and energy intensive, however. Economizer malfunctions and certain airflow restrictions, which are a big source of energy waste, do not cause comfort problems and are more costly to address.

Because refrigerant data can be difficult to obtain accurately, the Refrigerant Cycle approaches have only moderate reliability. While Airside data can also be difficult to accurately obtain, Qualitative and Timeseries-Based approaches, which do not require the same degree of accuracy as Quantitative approaches, might be considered somewhat more robust. Power-based approaches have somewhat less difficulty during installation, and are considered reliable.

Ease of Deployment

The deployment path for Timeseries-based methods is more limited than for the other methods. Because they require a lengthy period of correct operation for training and cannot be used in a commissioning-type service, they can only be deployed in an ongoing performance monitoring or maintenance service.

Other Maintenance Benefits

From a Title 24 perspective, maintenance benefits are an added bonus. All of the tools that identify regular maintenance issues, such as charge and fouling, will provide benefits to the team that maintains the building. The hybrid method that identifies issues such as nighttime operation would provide less of a maintenance benefit.

SUMMARY

Findings from this research project indicate that the use of fault detection and diagnostics (FDD) for rooftop packaged air conditioners (RTUs) has the potential to reduce both energy use and costs.

FDD systems are considered to have a useful life of 15 years. Therefore, the project team calculated estimates for annual energy savings and the resulting value of savings over 15 years, expressed as a present value. Although the savings returned due to FDD systems are realized over a 15-year life, costs are fixed and must be paid at the time of installation and maintenance. By subtracting the costs from the present value of the cumulative savings, the project team calculated the net financial benefit of the measure. The results are promising. The statewide savings are significant, with a 15-year life cycle net savings of over $8 million for California buildings, with a benefit/cost ratio of 2.0. Thus, it was found that FDD for RTUs is a cost-effective measure, appropriate for inclusion in Title 24.

By providing a comprehensive classification for available and hypothetical FDD tools, this project has been able to identify which approaches seem the most promising; that is, which available tools might be suitable for marketization or for inclusion in standards.

Highest Priority Approaches

This process has identified five approaches that appear to be most likely to be appropriate.

1. Power Qualitative

One of the high-scoring approaches is the Power Qualitative approach. The power profile of the unit is compared with target values stored into the controller for the different phases of the system. This is able to detect a large range of refrigerant and airside problems, in addition to electrical and controls faults. This approach has many benefits. It can be quite cost-effective, since it requires only one sensor and can detect a large number of faults that create energy waste in a large percentage of buildings. It would be difficult to install incorrectly, since it only has one sensor, and it can start immediately in detecting faults (without the requirement for a training dataset). Such a tool would provide a great deal of information to building operators and service contractors. NILM, developed by MIT, is an example of this approach.

2. Hybrid Airside/Power Timeseries-Based

Another high scoring approach is the Hybrid Airside/Power Timeseries-Based approach, which uses a dataset consisting of airside and power data to identify a limited set of faults. The faults include overall efficiency degradation, capacity degradation, operation during unoccupied times, and excessive cycling. While it cannot identify some of the faults that are identified by most of the other approaches, addressing this set of faults can be expected to save quite a bit of energy. The simplicity of this approach is appealing, and it should be quite reliable. Because it cannot be used in a commissioning-like service, it is considered less deployable, and because the faults it detects are "silent" faults that do not affect comfort or equipment condition, it may not be considered highly marketable. The Low-Cost SMDS proposed by PNNL is an example of this approach.

3. **Power Timeseries-Based**

   This approach requires looking at power at relatively high sampling frequency in order to detect faults that are expressed during transients, in addition to those found by looking at mean values. It requires only one datapoint, but high frequencies require a different processing platform, increasing the cost. It should be able to detect a long list of faults and save quite a bit of energy. Because of its simplicity, it will be quite reliable, and it will provide a great deal of maintenance information to service providers. The fact that it cannot be used in a commissioning-like service makes it somewhat less deployable. The Low-Cost NILM developed at MIT and the Power Analyzer being developed by Virtjoule are examples of this approach.

4. **Airside Qualitative**

   The variation in Airside parameters is compared with predefined acceptable ranges to detect faulty operation. This can detect important and common issues such as economizer faults, refrigerant charge errors, and coil fouling. It is reliable, due to the fact that the data inputs have less stringent accuracy requirements. The only downside to this method is its cost-effectiveness. Care will have to be taken to ensure that tools in this category are cost-effective. The SMDS developed by PNNL is an example of this approach.

5. **Airside Timeseries-Based**

   This system logs the system state for different input conditions and defines routine patterns. When a fault occurs, such as economizer errors, charge errors, or coil fouling, it can be detected as a deviation from the pattern. These models have the benefit of simplicity, and the ability to detect important and frequent faults. They too have only moderate cost-effectiveness, and care will have to be taken to ensure that tools are cost-effective. Because they require a long period of proper operation to train the system, their deployment model is less obvious. Sensus MI is an example of this approach.

While this report has characterized and evaluated generic and "hypothetical" approaches to FDD, it is certainly possible that individual approaches can overcome some of the hurdles faced by their category of approach. For example, if the cost and complexity of refrigerant-side measurements could be reduced, they could be very good candidates for code inclusion. FDSI's Insight is an example of an approach that may have promise if it can use existing sensors.

Title 24 Outcome

The research from this report was used for Phase IV of the Public Interest Energy Research (PIER) project Fault Detection and Diagnostics - Moving the Market and Informing Standards in California. A code proposal was submitted in conjunction with the Codes and Standards Enhancement (CASE) project and the project team participated in the Energy Commission's process for supporting the proposal. **This work led to a mandatory measure approved for the 2013 revision of the Title 24 commercial building energy standards.**

The measure will require that all air-cooled package, split system, and VRF units with economizers, at sizes 4.5 tons and above, have a minimum set of fault detection alarms aimed primarily at the economizer. As important, is the requirement that the fault notification must be communicated off the roof. The fault reporting mechanism and destination are not prescribed. If adopted, this first FDD code requirement may have an impact on the national RTU market when the revised Title 24 standard comes into force in January 2014.

The faults to be reported include:

- Sensor failure or fault
- Not economizing when it should
- Economizing when it should not
- Damper not modulating
- Excessive air flow

The limits to applying the new standard across the fleet of RTUs comes from the control design of the unit. Approximately 70% of existing RTUs are electromechanically-controlled, with the balance microprocessor-controlled. The above listed faults can be detected in both types of units. Additional alarms such as refrigeration cycle problems including high or charge and low or high pressure, can only be enabled in microprocessor-controlled units and thus were not accepted in the final T24 language.

This Title 24 FDD measure has also been proposed to the NW Energy Codes Group for its consideration. NEEA staff is part of the group and should be in strong support of the proposal. If the NW states adopt this requirement, it will provide impetus for additional states to adopt since it will be clear that there will be equipment coming to market to meet the required standard. The Title 24 FDD measure is also being proposed in the 2015 revision of the IECC and the IgCC.

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Appendices

A. FDD Stakeholder Interviews

B. FDD Energy and Demand Savings

C. Title 24 FDD Standard for Rooftop Units

APPENDIX A: FDD STAKEHOLDER INTERVIEWS

Public Interest Energy Research (PIER) Program
PROJECT REPORT

Fault Detection and Diagnostics: Moving the Market and Informing Standards in California

A1: Interviews with Key Stakeholders

WCEC
WESTERN COOLING EFFICIENCY CENTER

A Report of the Western Cooling Efficiency Center

RESEARCH • INNOVATION • PARTNERSHIP

Prepared for: California Energy Commission
Prepared by: Western Cooling Efficiency Center

MARCH, 2011
CEC-500-08-049

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PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Fault Detection and Diagnostics: Moving the Market and Informing Standards in California, by the Western Cooling Efficiency Center, is an interim deliverable for the *Fault Detection and Diagnostics: Moving the Market and Informing Standards in California Program*, conducted by New Buildings Institute (contract number 500-08-049). The information from this project contributes to PIER's Buildings End-Use Energy Efficiency Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

A crucial part of the prioritization of FDD tools is collecting intelligence from key stakeholders. In this report, Stakeholder Interviews, we describe the process of developing an interview guide and carrying out a small set of interviews. We summarize the interviews that were held, as well as provide the detailed responses to our list of questions.

Keywords: FDD, FDD Stakeholders, rooftop unit, air conditioning, fault detection, diagnostics, Title 24, energy standards.

Please use the following citation for this report:

Heinemeier, Kristin, (WCEC), Mark Cherniack (NBI), and Julien Bec (UCD). 2010. ***Fault Detection And Diagnostics, Moving The Market And Informing Standards In California.*** California Energy Commission.

Introduction

Objectives

The objectives of the overall Fault Detection and Diagnostics, Moving The Market and Informing Standards In California Deliverables project are:

- To identify appropriate technology for identifying and diagnosing faults in commercial building Rooftop HVAC Units (RTUs).
- To develop a proposal for a standard that would require this Fault Detection and Diagnostics (FDD) for Title 24.
- To get industry feedback on this proposal.
- To revise the proposal, and submit it to the Title 24 process.

Approach

Phase I

- Obtain input from industry stakeholders on desired capabilities of FDD tools and service models for making best use of FDD tools.

Phase II

- Identify the faults that occur in RTUs and their impact and frequency, to estimate the degree of savings made possible by FDD tools.
- Prioritize those faults to determine which are most likely to be cost effectively diagnosed and addressed.
- Identify diagnostic approaches that can be used to detect these faults.
- Define a set of criteria for the attributes an approach must have to be likely to be successful in the market place or to be successfully implemented in California's Title 24 energy code.
- Evaluate the potential approaches according to these criteria and identify potentially successful approaches, and describe the currently available tools that utilize these, and the Energy and Demand Savings potentially.

Phase III

- Create a "Minimum FDD Capability Requirements" document that summarizes and describes the requirements for a tool that could be incorporated in Title 24, including a description of the required functionality, and an outline of the acceptance tests that would be required to document installed functionality.
- Hold an Industry Roundtable to obtain industry feedback on this draft.

Phase IV

- Develop and submit a code proposal, and follow the CEC process to support the proposal.

In the second Phase of this project, “Fault Detection And Diagnostics, Moving The Market And Informing Standards In California Deliverables: B: FDD Prioritization,” we will identify and prioritize the faults that can be detected by a set of currently (or shortly) available diagnostic tools, and will evaluate the available tools.

One crucial part of this prioritization is collecting intelligence from key stakeholders. In this report, we describe the process of developing an interview guide and carrying out a small set of interviews. We summarize the interviews that were held, as well as provide the detailed responses to our list of questions.

In the third Phase, we will develop a draft specification for new requirements for FDD in Rooftop Units. We will also hold an industry roundtable to present the draft to a set of industry actors, and obtain their feedback. The following phase will consist of drafting a proposal for a standard and following the CEC Title 24 review process.

Background

Remote and automated Fault Detection and Diagnostic (FDD) tools have the potential to save considerable energy in California fleet of existing commercial rooftop air conditioning units (RTUs). The market for these systems has not yet materialized, however. Tools have been available for larger systems for some time, although even these have not enjoyed a significant market share. In RTUs, there are fewer tools available, and little to no market share.

Since RTUs cool over 70% of the commercial square footage in California, they are a significant source of energy consumption and peak demand. Under the best of circumstances, RTUs are not as efficient as larger built up systems. However, in reality, they are even less efficient. Many market failures have led to a lack of quality in installation and maintenance of these units, and their performance is suffering. Most RTUs have some sort of fault that is increasing their energy use. If these faults could be found and addressed, then a significant energy savings could be realized.

Interview Guide

The WCEC and NBI team developed an interview guide, intended to gauge the acceptability of FDD tools for RTUs. The guide is provided in Attachment 1. The guide consists of three separate sections.

- *Section 1: What is your Service Business like?* This is intended to find out about typical service models, and the business environment into which FDD will have to fit. No mention is made in this section of FDD.

- *Section 2: Here’s FDD…* This is intended to give the interview participants a common grounding in what is meant by FDD tools.

- *Section 3: How Do or Would You Use FDD?* This section is intended to establish whether or not the participant has used any FDD tools, and why or why not. It is also intended to identify the necessary characteristics that would make FDD usable by them.

Summary of Interviews

Two interviews were held on December 18 and December 21, 2009 respectively. Each of these interviews included two participants. Attachments 2 and 3 present the raw responses from the interview participants.

Some of the major themes that emerged from these interviews include:

What is your service business like?

- How important is the service contract?
  - Best business is through repeated relationship.
  - Maintenance contracts offer recurring revenue, business year round.
  - Referrals common.
  - Some firms offer a full coverage guarantee – ~3 times the price of maintenance
  - Retention rate is important.
  - It's hard to sell a maintenance contract.
  - Some firms offer a 2 year warranty on installation is customer signs a service contract.
  - Best arguments to get people enroll into a maintenance contract: routine vs crisis. Most agree, but still need to be economically persuasive. "we're taking care of it for you"
  - more of a collaborative work: ask you while planning yearly budgets, etc…
- What are the most common problems?
  - Belt problems, bearings, contactors, capacitors, fan motor, compressor, missing filters, filter change, low air, freezups, heat exchanger failure, expansion valve takes out compressor, refrigerant leaks, operating pressures.
  - Overcharging is a training issue.
  - Depends on the quality of maintenance.

    - It's possible to put sensors on everything, but would have more issues with the sensors than with the parts in the first place.

- Special notes on economizers?
    - It is the first thing you disable. Complexity vs. benefits: it costs $500-1000 to fix it. If disabled: everybody gets what he wants. Possible because of cheap energy.
    - economizer working is quite complex. Setting it correctly is a challenge.
    - not noticed by the customer. Noticed during maintenance, or customer complaining about low cooling. Service technician: fresh air over dramatized. => need for less fresh air., ie less bills most of the time. Customers often prefer to have it disabled than fixing it.
    - if the customer knew the cost of disabling the economizer, it could be possible to make a value proposition. Right now they don't see the benefit. W: Long payback.
    - lack of public awareness. Have to do the check, hard to convince.
    - The customer is still comfortable, so it's a hard sell.
- How important is metering?
    - Car analogy: mpg information very educative.
    - Need a monetary conversion process: EER to $. Hard to do with energy efficiency.
- Why would a customer replace a unit?
    - Old and broken down (for example compressor out).
    - Age and cost of repair taken into account. "Under 500$ policy": if it costs less than $500, repair it.
    - In a house: 12 years and above compelling to replace it.
    - Another significant cause could be a hard to fix coil failure.
    - Window of opportunity with fluid change=> if some equipment is not on sale anymore, need to change the whole unit. More significant with split system, because each half is sold independently. If one needs to be replaced, and only the new refrigerant type is available, then the other needs replacement too.
    - many units in a complex, for example. Can be planned during the year. Dismounted equipment used as spare for the rest of the units.

- On RTU, parts available for a long time. Fluid available. Concern for change if many RTUs at the same location and some are dead. All may be replaced to avoid a mix of refrigerants.

- Part of a building renovation. Reroof, ownership change, tenant change. Financial transaction already taking place. Part of the negotiation to extend or renew the lease. Depreciation calculation by large property owner.

- Customers do not consider energy operating costs directly, fixed/changed if broken. =>likely to go with the fastest repair. Energy efficiency is a secondary argument.

- What are the maintenance cost constraints?
  - Can't bid 1 hour for preventive maintenance. Motivation: Try to avoid service call between now and next regular service.
  - It's typical that a maintenance tech will get 20 hours/week to do service, and has to get as many customers as he can.
  - typically 5-6 calls a day. Compressor replacement: 4 hrs, but simple maintenance and diagnostics: 4-6/day
  - better diagnostics on the system makes you faster and more confident.
  - we try to do 2-1/2 calls/day (<10 tons).
  - 5 calls if they're simple, if its superheat pressure or economizer 3-4 per day.
- OEM's provide some things for diagnosing faulty operation. Not much on the cooling side. usually used by technicians if present, but not very predominant right now.

How do you or would you use FDD?

- Are you using tools now?
  - Most organizations currently not using any kinds of tools like FDD
  - One we interviewed worked with three tools in Air-Care Plus. They were hit and miss. A lot of the reports didn't make sense. It works better with small equipment (eg, temperature probes). Depends on ambient and return conditions. A lot of cables and connections. It's hard to be profitable. Existing customers will ask "why didn't you find it before?". It's good to use when doing compressor changeouts for refrigerant charge: we bought 2 tools on our own.
- What are the benefits to the customer?
  - Better interaction with the contractor. Shows professionalism.

    - long term performance monitoring may help to “prepare” the client for heavier/preemptive interventions

- What would you like in a tool:

    - an automated report generation every so often (month?) sent to a specific person.

    - time it with energy bills so that customers are more aware.

    - Do not overload clients/technicians with data

    - An indication about performance, another one about energy consumption.

    - Different information levels:

        - “idiot light”

        - alarm if efficiency goes under a certain threshold

        - efficiency for each unit

    - Tool needs to be portable.

    - log all activity

    - Daily updates, although there’s a nuisance factor. Safeway, for example, gets Benchmark variance data, monthly on different variables.

- Will these tools reduce the number of service calls?

    - Do not see any reduction of field trips: need to factor in false alarm

    - am I avoiding more calls, or creating more calls? How many false positives?

    - Each layer of complexity adds possible faults. => the increased maintenance may counterbalance all the energy benefits.

    - On a service contract, false alarms as a cost for the contractor.

    - The system must actually bring what it promises.

    - A good solution should cost less than $100

    - Can’t reduce service calls to 2/year because of filters and belts.

- Would customers pay a 5-10% premium?

- Can see a premium of 10% for a very good field diagnostic device.
- If they have a critical environment.
- Need a more sophisticated customer.

- What type of customers would be most interested?
  - Maintenance contract customers have a long term view, and do analysis on a whole building level.
  - Higher end workers, like doctors/ lawyers would be most interested in this kind of service. High end restaurants. Retails with food safety issues
  - process, server room, financial component is important.

Attachment 1: FDD Interview Guide

What is your service business like?

1. What constitutes RTU service in the field?

2. How is your service business structured?

3. What problems are the most common or the most important (why?) causes of service calls?

4. Have you ever told an owner that their RTU was on its last legs? What symptom were you responding to? What did the customer say? What data did you need to make this call and convince the owner?

5. How long is a typical service call/how many service calls can a technician make in a day? What influences this?

6. What is the nature of RTU service marketing [how is service marketed? How is service delivered-scheduled calls/on demand only for some/other? How is service linked to product sales]

7. What tools do your techs use to diagnose faulty or less-than-optimal performance?

8. What tools do the OEM's provide for diagnosing faulty operation?

9. What tools do the OEM's provide for performance monitoring?

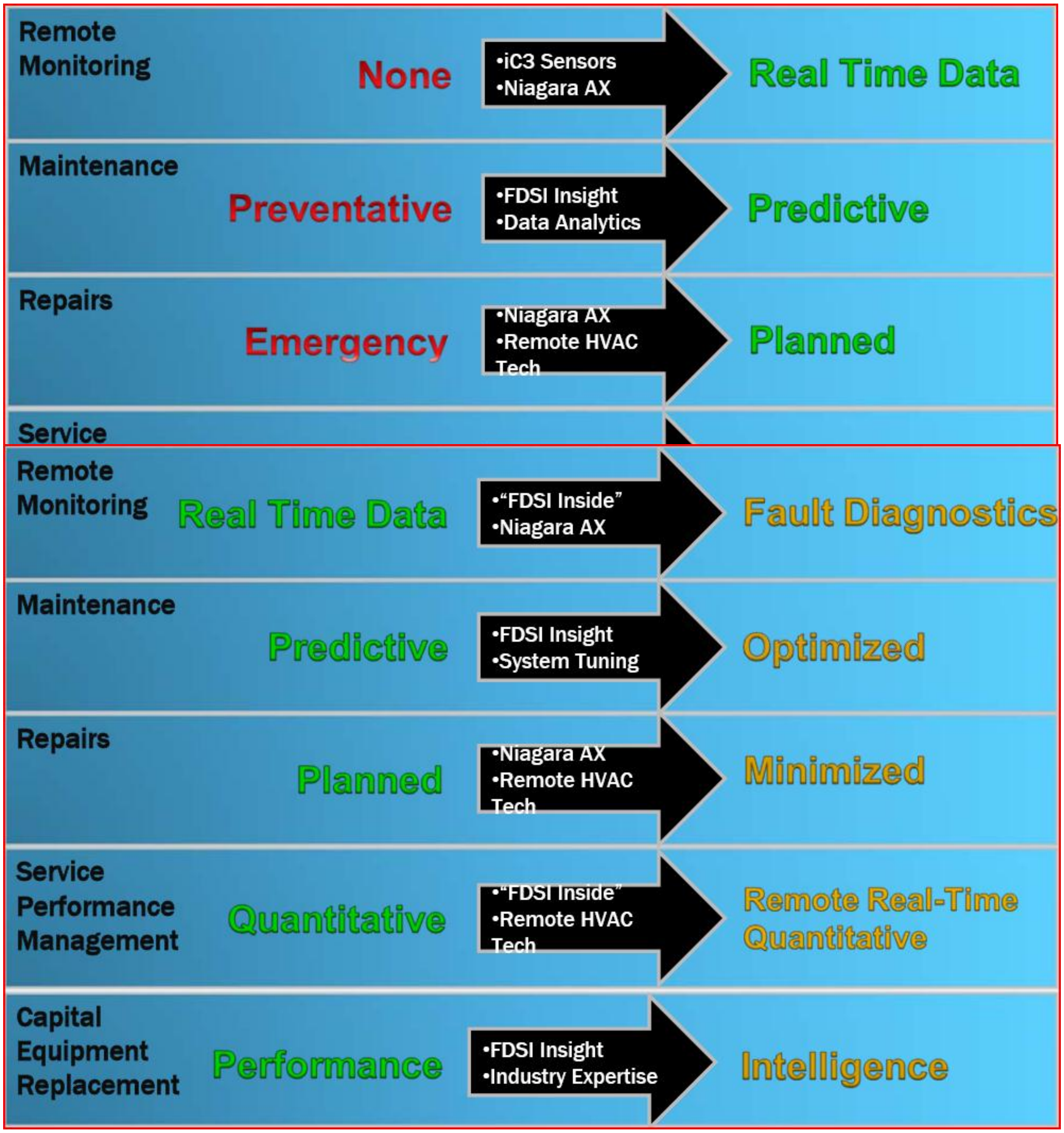
10. Do your techs use these tools? If not, why not?

11. What (related to your RTU service business!) keeps you up at night?

Faults

Categories	Hard fault	Degradation fault	Fault Prediction
Description	Loss of a function/whole unit	No loss of function, but not performing as expected	Identify a unit that is near the end of its useful life
Monitoring	Sensors and Simple Alarms	Performance Monitoring	Characteristic performance metrics and Inspection
Detection	Comfort not maintained	Models for symptoms or performance metrics	Models for symptoms and Inspection
Diagnostics	Fault is easy, cause may be more difficult	Need for specific procedure/tools	Fault is easy, cause may be more difficult
Annunciation	Technician during Service Call, or Remote to Service Center with Data Mining	Remote to Service Center	Technician during Service Call, or Remote to service center

Bank of America Intelligent Command and Control Center



How do you or would you use FDD?

1. Are you or your organization currently using any kinds of tools like FDD?

2. Can you imagine using FDD tools in your service business? How? What's the business model? How would you change your service offering?

3. Would you be more interested in hard faults, degradation faults, or fault prediction?

4. Would you be more interested in monitoring, fault detection, or diagnostics?

5. What value would it bring to you? (reduce the number of trips required, reduce the length of a service call, …)

6. What value would it bring to your customer? (amount of energy savings, improved uptime,…)

7. How much of a premium would your customers be willing to pay, (or how much of a discount would they need to see), to be provided this service? (One time capital cost/ monthly/ quarterly/ annual fee-based?)

8. How much would you be willing to pay to have this tool available?

9. What types of customers do you believe would be most interested in this kind of service?

10. Would you be interested in remote monitoring of RTUs? [dependent on customer size or would you like for all customers?]

11. What performance monitoring/FDD information do you think are most important in terms of optimizing performance/efficiency?

12. What information would you like to see on an FDD/PM GUI/dashboard?

13. If you could design an RTU performance monitoring system with remote access, what would be included as features?

14. Do you have any customers who you think we should interview?

Attachment 2: Interview 1

Participants:

Erik Emblem (E) Cal SMACNA and Rick Wylie (W) Beutler Corp.
December 18, 2009

Background

E: A Consultant with the California Sheet Metal Workers. Contractor background 7 years service.
70% of the client's activity. Clients expectations: Reliability dependability consistency.
Union: 625 contractors in California, 50 union members.
From fabrication companies to HVAC global suppliers
W: Installation technician. Done some service work.
Maintenance intended as "maintenance agreement"
Commercial: more likely to see the value of maintenance. Some have their own maintenance staff (filter change, simple parts replacement, etc…)

What is your service business like?

1. What constitutes RTU service in the field?

   W: on the phone, ask for show up cost. Some easy things can be fixed on the spot. For the rest, price proposition for fixing. No need for permits for part swaps
2. How is your service business structured?

   W:Business through repeated relationship.
   E: lot of contact through the internet. Relationship: established from quite some time (family recommendations: inter generational). Sticker on the heater.
   Nate (?) study: demographics on the first call. => more feminized…
   W: New commercial practices: price based competitive bid on maintenance contract.
   If maintenance contract, typically repairs not taken into account, but discount applied. Some higher end /specific application may have a partial coverage of repairs.
3. What problems are the most common or the most important (why?) causes of service calls?

   W: less leaks than in split systems. In order of occurrence: Belt problems, bearings, contactors, capacitors fan motor, compressor (rare but significant) Missing filters
   Q: how do you know bearings are shot?
   W: from the noise, can be seen. More generally, accurate service allows to see a lot
   Q: what if it could be remotely detected?
   W: possible to put sensors on everything, but would have more issues with the sensors than with the parts in the first place.
   Q: What about economizer issues?
   W: first thing you disable. Complexity vs. benefits: 500-1000$ to fix it. If disabled: everybody gets what he wants. Possible bc cheap energy.
   Q: snap disk thermostat; damper motor (question of Mark regarding the link btw snap disks and motors, not really understood)
   W: whatever the piece, economizer working is quite complex. Setting it correctly is a

challenge.
Q: does the customer asks to fix the economizer?
W: not noticed by the customer. Noticed during maintenance, or customer complaining about low cooling. Service technician: fresh air over dramatized. => need for less fresh air., ie less bills most of the time. Customers often prefer to have it disabled than fixing it.
E: if the customer knew the cost of disabling the economizer, it could be possible to make a value proposition. Right now they don't see the benefit. W: Long payback.
E: lack of public awareness. Have to do the check, hard to convince.
W: on the customer side, people would rather spend on a solar system, even if less efficient: importance on metering the production. Car analogy: mpg information very educative. Importance of metering. Monetary conversion process. EER to $. Hard to do with energy efficiency?

4. Have you ever told an owner that their RTU was on its last legs? What symptom were you responding to? What did the customer say? What data did you need to make this call and convince the owner?
W: 1- old and broken down (for example compressor out). Age and cost of repair taken into account. In a house: 12 years and above compelling to replace it. Another significant cause could be a hard to fix coil failure. Window of opportunity with fluid change=> if some equipment is not on sale anymore, need to change the whole unit. More significant with split system, because each half is sold independently. If one needs to be replaced, and only the new refrigerant type is available, then the other needs replacement too.
Other case: many units in a complex, for example. Can be planned during the year. Dismounted equipment used as spare for the rest of the units.
On RTU, parts available for a long time. Fluid available. Concern for change if many RTUs at the same location and some are dead. All may be replaced to avoid a mix of refrigerants.
2- part of a building renovation. Reroof, ownership change, tenant change. Financial transaction already taking place. Part of the negotiation to extend or renew the lease. Depreciation calculation by large property owner.
Q: how to assess the remaining life on the unit. Customers arrive with preconditioned ideas. Like, "under 500$ policy".
Q: consider energy operating costs? W: not directly, fixed/changed if broken. =>likely to go with the fastest repair. Energy efficiency is a secondary argument.
E: Carfax like report: click a few things, and gives you a "number"
W: best customer: maintenance customer. Long term view. Analysis on a whole building level.
Q: what arguments to get people enroll into a maintenance contract.
W: routine vs crisis. Most agree, but still need to be economically persuasive. "we're taking care of it for you"
E: more of a collaborative work: ask you while planning yearly budgets, etc.
Q: advice for good deals?
E: give the clients the information they need

5. How long is a typical service call/how many service calls can a technician make in a day? What influences this?
W: typically 5-6 calls a day. Compressor replacement: 4 hrs, but simple maintenance and diagnostics: 4-6/day
Q: productivity gains of integrated diagnostics?
W: better diagnostics on the system makes you faster and more confident.

6. What is the nature of RTU service marketing [how is service marketed? How is service delivered-scheduled calls/on demand only for some/other? How is service linked to product sales]

7. What tools do your techs use to diagnose faulty or less-than-optimal performance?
W: Temperature probe, gages, amp-meters. So much variation out there that it is tough to have a standardized protocol/tools. Some “art” is involved!

8. What tools do the OEM’s provide for diagnosing faulty operation?
W: Some things provided on the controllers. Mainly on the furnace side. Not much on the cooling side. Usually used by technicians if present, but not very predominant right now.

9. What tools do the OEM’s provide for performance monitoring?

10. Do your techs use these tools? If not, why not?

11. What (related to your RTU service business!) keeps you up at night?
W: Nothing specific to RTUs. More general business management: trained workers, customer interaction.
E: noise transfer can be an issue, but outside of this, no problem.
W: automated report generation every x (month?) sent to a specific person.
E: time it with energy bills so that customers are more aware.
W: on big businesses: numbers add up and it starts to be worth investing. And image issues.

How do you or would you use FDD?

1. Are you or your organization currently using any kinds of tools like FDD?
   No

2. Can you imagine using FDD tools in your service business? How? What’s the business model? How would you change your service offering?
   W: could be a benefit
   E: depends on how it is packaged. Do not overload clients/technicians with data
   Do not see any reduction of field trips: need to factor in false alarm
   W: am I avoiding more calls, or creating more calls? How many false positives? Each layer of complexity adds possible faults. => the increased maintenance may counterbalance all the energy benefits. On a service contract, false alarms is a cost for the contractor.

3. Would you be more interested in hard faults, degradation faults, or fault prediction?

4. Would you be more interested in monitoring, fault detection, or diagnostics?

5. What value would it bring to you? (reduce the number of trips required, reduce the length of a service call, …)
   E: No real reduction of trips expected (see 2)
   W: Interventions may be more efficient. The system must actually bring what it promises.

6. What value would it bring to your customer? (amount of energy savings, improved uptime,…)
   E: better interaction with the contractor. Shows professionalism.
   W: long term performance monitoring may help to "prepare" the client for heavier/preemptive interventions

7. How much of a premium would your customers be willing to pay, (or how much of a discount would they need to see), to be provided this service? (One time capital cost/ monthly/ quarterly/ annual fee-based?)
   W: 10% for a very good field diagnostic device.

8. How much would you be willing to pay to have this tool available?
   W: to many possible situations to give a figure

9. What types of customers do you believe would be most interested in this kind of service?
   W: higher end workers, like doctors/ lawyers. High-end restaurants. Retails with food safety issues

10. Would you be interested in remote monitoring of RTUs? [dependent on customer size or would you like for all customers?]
    W: only way to justify an added cost. If technician has to show up, even a good solution should cost less than $100 (see 7)

11. What performance monitoring/FDD information do you think are most important in terms of optimizing performance/efficiency?

12. What information would you like to see on an FDD/PM GUI/dashboard?
    W: An indication about performance, another one about energy consumption.

13. If you could design an RTU performance monitoring system with remote access, what would be included as features?
    E-W: Different information levels:

-"idiot light"
- alarm if efficiency goes under a certain threshold

- efficiency for each unit
- log all activity

14. Do you have any customers who you think we should interview?
    E: see about national restaurant association

Attachment 3: Interview 2

Participants:

Denny Mann (D) Marina Mechanical and Russ Donicci (R) Mechanical Air Service
December 21, 2009

Background

D: Service ($4Million) and Construction
R: $2Million business, 80% construction. Residential component is high end. Service, retrofit, clean rooms. 60% new, 40% service

What is your service business like?

1. What constitutes RTU service in the field?

D: Maintenance contracts, recurring revenue, business year round. General operations for retrofit. Commercial, light industrial. Not much refrigeration. 14 trucks. Total cost not hourly rate. Contract <100,000 sqft. Unless on staff, 95% on contract.
R: It's hard to get a maintenance contract.

2. How is your service business structured?

D: referrals common. Contract for 4 times per year. $500 pre approved, avoids truck roll. Full coverage guarantee – 3 times the price of maintenance.
Q: Callbacks different between manufacturers?
D: No. Tho a few years ago York had >20%.
D: we provide a Warranty of 1 year
R: Tenant aggravation, maintenance is often a "loss leader", where contractors do bad installs and make up on service. It's typical that a maintenance tech will get 20 hours/week to do service, and has to get as many customers as he can.

3. What problems are the most common or the most important (why?) causes of service calls?

D: Non-PM: filter, low air, freezups, heat exchanger failure. Depends on the quality of maintenance.
Can't bid 1 hour for preventive maintenance. Motivation: Try to avoid service call between now and next regular service.
See study by Jones Long LaSalle, BOMA Studies.
R: Electrical, contactors, expansion valve takes out compressor, refrigerant leaks, operating pressures. Training issue: don't overcharge.
D: Economizers, it costs $100 to fix the actuator. The customer is still comfortable, so it's a hard sell. We use Honeywell software. We talked with Adrienne Thomle, the 7650 costs $20 and the 7660 costs $24.

4. Have you ever told an owner that their RTU was on its last legs? What symptom were you responding to? What did the customer say? What data did you need to make this call and convince the owner?

5. How long is a typical service call/how many service calls can a technician make in a day? What influences this?
R: budget for capital improvement. 20% energy savings. Good relationship – fan was looking wornout and there was bearing noise. Checked on parts availability, reduced disruption for tenants. Other contractors are looking for what you missed.
D: we try to do 2-1/2 calls/day (<10 tons).
R: 5 calls if they're simple, if its superheat pressure or economizer 3-4 per day.

6. What is the nature of RTU service marketing [how is service marketed? How is service delivered-scheduled calls/on demand only for some/other? How is service linked to product sales]

7. What tools do your techs use to diagnose faulty or less-than-optimal performance?
D: worked with three tools in Air-Care Plus. They were hit and miss. A lot of the reports didn't make sense. It works better with small equipment (eg, temperature probes). Depends on ambient and return conditions. A lot of cables and connections. It's hard to be profitable. Existing customers will ask "why didn't you find it before?". It's good to use when doing compressor changeouts for refrigerant charge: we bought 2 tools on our own.

8. What tools do the OEM's provide for diagnosing faulty operation?
The new Lennox RTU tells you when it went off on high head, delta T on coil, pressures of system.

9. What tools do the OEM's provide for performance monitoring?
10. Do your techs use these tools? If not, why not?

11. What (related to your RTU service business!) keeps you up at night?

How do you or would you use FDD?

1. Are you or your organization currently using any kinds of tools like FDD?
   D: We use Service Assistant
   R: we use thermal imaging

2. Can you imagine using FDD tools in your service business? How? What's the business model? How would you change your service offering?
   R: some customers maintain different things. Degradation, re remote service assistant. Change more level of service. Clerk can't interpret data. Customer: predictive, downtime, energy costs. We are trying to get into the energy component.
   AB1103 requires the Energy Star Rating, it's hard to get things like the number of PCs.

Carbon footprint is a motivator. Need a 5 year SPT on equipment. Would customers pay a 5-10% premium? If they have a critical environment. Retantion rate is important. Need a more sophisticated customer. Service assistant $3000. Tool needs to be portable. Can't reduce service calls to 2/year because of filters and belts. We offer a 2 year warranty on installation is customer signs a service contract.

3. Would you be more interested in hard faults, degradation faults, or fault prediction?

4. Would you be more interested in monitoring, fault detection, or diagnostics?

5. What value would it bring to you? (reduce the number of trips required, reduce the length of a service call, …)

6. What value would it bring to your customer? (amount of energy savings, improved uptime,…)

7. How much of a premium would your customers be willing to pay, (or how much of a discount would they need to see), to be provided this service? (One time capital cost/ monthly/ quarterly/ annual fee-based?)

8. How much would you be willing to pay to have this tool available?

9. What types of customers do you believe would be most interested in this kind of service?
   D: process, server room, financial component is important.

10. Would you be interested in remote monitoring of RTUs? [dependent on customer size or would you like for all customers?]

11. What performance monitoring/FDD information do you think are most important in terms of optimizing performance/efficiency?
    D: Service assistant type information: performance, efficiency, Supply and return temps, amps on components to confirm what's running. Go back and look at trends
12. What information would you like to see on an FDD/PM GUI/dashboard?
    D: Daily updates, although there's a nuisance factor. Safeway, for example, gets Benchmark variance data, monthly on different variables. Need to know how to use Carrier alarms.
    R: Traiing: manufacturer school if it's worthwhile, then teach what you learned.
13. If you could design an RTU performance monitoring system with remote access, what would be included as features?
14. Do you have any customers who you think we should interview?
    Kevin Napper, Safeway

APPENDIX B: FDD ENERGY AND DEMAND SAVINGS

Public Interest Energy Research (PIER) Program
PROJECT REPORT

Fault Detection and Diagnostics: Moving the Market and Informing Standards in California

A2: Energy and Demand Savings

A Report of the Western Cooling Efficiency Center

RESEARCH • INNOVATION • PARTNERSHIP

Prepared for: California Energy Commission
Prepared by: Western Cooling Efficiency Center

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ENERGY AND DEMAND SAVINGS

Fault Detection and Diagnostics (FDD) for Rooftop Units (RTUs) has been put forward as a new prescriptive measure in California's proposed 2013 Energy Efficiency Standard for Nonresidential Buildings—Title 24. As a part of the analysis performed for proposed Title 24 requirements, energy and demand savings attributable to FDD have been estimated for California commercial buildings.

This work was led by PECI under contract to the Heschong Mahone Group, with funding from the California investor-owned utilities Codes and Standards Enhancement (CASE) program. The energy modeling analysis was primarily funded under a contract with the California Energy Commission's Public Interest Energy Research (PIER) program led by New Buildings Institute in collaboration with the Western Cooling Efficiency Center and EnergySoft, LLC. PIER and CASE researchers worked closely together to review all aspects of the energy and demand analysis including inputs to, and results from, the modeling. This report is a detailed excerpt taken from PECI's deliverable to the CASE program, entitled: "2013 California Building Energy Efficiency Standards: Light Commercial Unitary HVAC."

The analysis was submitted in support of inclusion of RTU FDD as a prescriptive measure in the 2013 Title 24 revision and fully supported by the PIER and CASE research teams. Attributes of the analysis to estimate savings included:

- Building energy simulation in six representative California climate zones and seven prototype buildings of RTU faults that can be directly modeled in EnergyPro, which is a leading Title 24 compliance checking software product.
- Analysis of secondary literature to identify the EER penalty of other common RTU faults.
- EnergyPro modeling with and without these EER penalties to determine energy savings for the RTU faults that cannot be directly modeled in EnergyPro.
- Estimation of probabilities needed to project savings across a population of buildings, including:
    - Probability that the fault will occur. This included analysis of field data from over 17,000 RTUs in PECI's AirCare Plus RTU maintenance program to obtain fault prevalence data, and further analysis of these data to translate prevalence into annual incidence data.
    - Probability that faults will be detected by an FDD tool.
    - Probability that faults would have been detected without an FDD tool (the baseline).
    - Probability that faults will be addressed, once detected.
- Application of probabilities to individual building savings to estimate the savings potential across an entire population of buildings.
- Lifecycle cost analysis using time-dependent valuation of energy savings and including maintenance savings, as well as the estimated cost of FDD systems.

- Application of individual building simulations and probabilities to estimate savings across California: in a range of building types, in all California climate zones.

The results are promising. The statewide savings are significant, with a 15-year life cycle net savings of over $8M for California buildings, with a benefit/cost ratio of 2.0. Thus, it was found that FDD for RTUs is a cost effective measure, appropriate for inclusion in Title 24.

FDD for Light Commercial Unitary HVAC

2013 California Building Energy Efficiency Standards

July 29, 2011

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FIGURES

Acknowledgments

The California IOUs sponsored this report as part of their CASE (Codes and Standards Enhancement) projects. Stuart Tartaglia of PG&E was the project manager for this nonresidential CASE project. The Heschong Mahone Group (HMG) is the prime contractor and provided coordination of the nonresidential CASE reports. HMG and Jon McHugh (McHugh Energy Consultants) provided technical and editorial review.

Matthew Tyler and Amber Buhl of PECI performed most of the analysis and reporting presented here.

Martyn Dodd of EnergySoft led the energy simulations.

The authors would especially like to thank Mark Cherniack (New Buildings Institute) and Kristin Heinemeier (Western Cooling Efficiency Center) for their valuable and extensive collaboration on the FDD sections on behalf of their associated CEC PIER project.

Methodology

This section summarizes the methods used to collect data and conduct the analysis for this CASE report for the Fault Detection and Diagnostics (FDD) proposal.

Fault Detection and Diagnostics (FDD)

FDD is included in 2008 Title 24 as a compliance option. This proposal is to advance FDD as a prescriptive option.

Numerous HVAC faults were investigated in this study to determine the potential benefit of FDD systems in detecting these faults, including:

1. Air temperature sensor failure/fault
2. High refrigerant charge
3. Low refrigerant charge
4. Compressor short cycling
5. Refrigerant line restrictions/TXV problems
6. Refrigerant line non-condensables
7. Low side HX problem
8. High side HX problem
9. Capacity degradation
10. Efficiency degradation
11. Not economizing when it should
12. Damper not modulating
13. Excess outdoor air

Background and Literature Review / Secondary Data Mining

In this task we conducted a literature review to investigate the current state of the FDD market in terms of current product availability, product development, costs, faults detected, and fault incidence. An annotated bibliography summarizing this literature review is included at the end of this report in the section.

For the data mining task we relied on PECI's AirCare Plus (ACP) program, which provides incidence data for a number of HVAC faults. ACP is a comprehensive diagnosis and tune-up program for light commercial unitary HVAC equipment between 3 and 60 tons cooling capacity. This program has been active throughout the PG&E service territory since 2006 and throughout the Southern California Edison service territory since 2004. It includes inspection of the following HVAC components: thermostat controls, economizers, refrigerant charge, and airflow. The ACP program database includes over 17,000 RTUs with documented status of these HVAC components. This massive collection of HVAC data proved useful in identifying the incidence of various HVAC faults as described in the Analysis & Results section.

Based on the literature review and data mining, we defined the faults and the associated energy simulations to estimate the savings from detecting and fixing the faults. The remainder of this section provides this information.

Energy Savings

A series of EnergyPro energy simulations and corresponding TDV analysis were conducted to estimate the potential energy savings resulting from use of FDD. A representative sample of California climate zones were modeled, including: 3, 6, 9, 12, 14, and 16. The other California climate zones were not included in these energy simulations as they are sufficiently represented by the selected zones for the purposes of this research. Figure 1 indicates which climate zones the selected zones represent and Figure 2 shows a map of the climate zones.

Simulated climate zone	Maps to climate zones:
3	1, 2, 3, 4
6	5, 6, 7
9	8, 9, 10
12	11, 12, 13
14	14, 15
16	16

Figure 1 Climate Zone Mapping

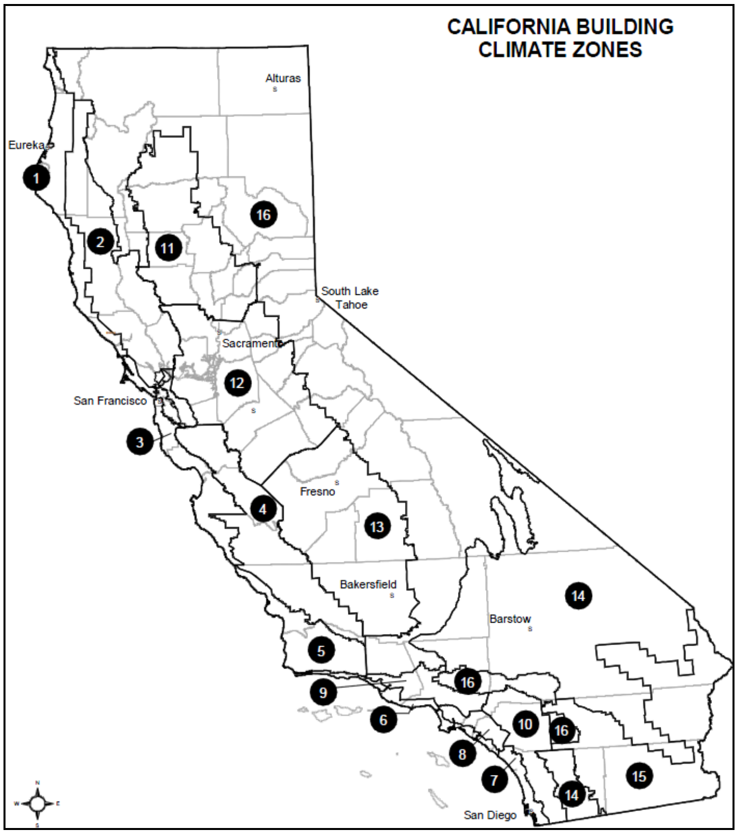

Figure 2 Climate Zone Map

Seven (7) prototype simulation models were developed for the analysis. Figure 3 summarizes a number of key inputs used in the energy simulations:

	Occupancy Type	Area (Square Feet)	Number of Stories	# HVAC Systems	Total tons	Avg sf/ton	Occupancy Schedule
Prototype 1	Fast Food	2,099	1	2	11	199	T-24 schedule
Prototype 2	Grocery	81,980	1	18	249	329	T-24 schedule
Prototype 3	Large Retail	137,465	1	22	286	480	T-24 schedule
Prototype 4	School	44,109	2	39	171	257	T-24 schedule
Prototype 5	Small Office	40,410	2	14	113	356	T-24 schedule
Prototype 6	Small Retail	8,149	1	4	25	330	T-24 schedule
Prototype 7	Large Office	112,270	2	10	421	267	T-24 schedule

Figure 3 Summary of Energy Simulation Models for FDD

Measure Cost

The cost of an FDD system is "*based upon the type of data that is required, the overall number of points required, any processing capabilities that must be added, and communications hardware and access. The principal cost incurred for FDD is for data collection. Depending on the method that is used, existing sensors installed in the RTU might be used. Care must be taken to ensure that the sensors are of sufficient accuracy* *and are installed in the appropriate location. In some cases, redundant sensors might be needed to take the place of the existing sensors."*[4]

The CASE authors contacted FDD system developers to identify the measure costs, which are reported in the section Analysis and Results.

Product Availability

There are a few tools currently on the market. A handful of other tools have been piloted but have not yet been introduced to the market as viable products, and yet others are under development. It is useful to describe the tools that are commercially available, available in pilot status only, or in the pipeline. Heinemeier et al. (2010) outlines the development status of various third party FDD systems as shown in Figure 4.

Tool Name	Status	Data	Model	Developer
FDSI Insight V.1	Available	Refrigerant	Quantitative	Field Diagnostics, Inc
Sensus MI	Available	Air	Qualitative	University of Nebraska
ClimaCheck	Available	Refrigerant	Quantitative	ClimaCheck Inc.
SMDS	Pilot	Air	Qualitative	Pacific Northwest National Lab
NILM	Pilot	Power	Qualitative	Massachusetts Institute of Technology
Low Cost NILM	Pilot	Power	Timeseries	Massachusetts Institute of Technology
Sentinel/Insight	Beta	Refrigerant	Quantitative	Field Diagnostics, Inc
Virtjoule	Developing	Power	Timeseries	Virtjoule Inc.
Low Cost SMDS	Developing	Air-Power	Timeseries	Pacific Northwest National Lab

Figure 4 Third Party FDD System Status

Heinemeier describes each system's capability for detecting specific faults as shown below in Figure 5. The list of HVAC faults investigated for this project are mostly included as faults that FDD systems can detect. For example, seven of these nine FDD systems can detect low airflow, six systems can detect low/high refrigerant charge, and eight can detect compressor short cycling. Three faults investigated for this project are not directly included on this list of detected faults. They are refrigerant line restrictions, non-condensables, and high side heat exchange problems. These problems lead to other faults that are included in this list (performance degradation, insufficient capacity); so these faults will be indirectly detected.

---

[4] Heinemeier, Kristin, (WCEC), and Julien Bec (UCD). 2010. Fault Detection And Diagnostics, Moving The Market And Informing Standards In California: FDD Prioritization. California Energy Commission.

O	Basic FDD
X	Extended FDD

	FDSI Insight V.1 Production	Sensus MI	ClimaCheck	SMDS	NILM	Low Cost NILM	Sentinel/Insight Beta Testing	Virtjoule	Low Cost SMDS
Low Airflow	O	O	O		O	O	O	O	
Low/High Charge		O	O		O	O	O	O	
Sensor Malfunction	O	X	O	O			O	X	
Economizer not Functioning	O	X	X	O			O	O	
Compressor Short Cycling	O	X	O		O	O	O	O	O
Excessive Operating Hours	O	X	O				O	O	O
Performance Degradation		O	O	O	O	O	O	O	O
Insufficient Capacity	O	X	O				O	X	O
Incorrect Control Sequence	O	X	O		O	O	O	O	
Lack of Ventilation	O	X		O			O	X	
Unnecessary Outdoor Air	O	X	X	O			O	X	
Control Problems	O	X	O	O			O	O	
Failed Compressor	O	O	O	O	O	O	O	O	
Stuck Damper	O	O	O	O			O	X	
Slipping Belt	O	O	O		O		O	O	
Leaking Valves			O		O		O	X	
Unit Not Operational	O	X		O	O	O	O	O	O

Figure 5 Third Party FDD System Faults Detected

In addition to these third party systems, a number of HVAC OEMs offer fault detection on some of their currently available models. These faults include:

- Air temperature sensor failure/fault
- Low refrigerant charge
- Not economizing when it should/shouldn't
- Damper not modulating
- Excess outside air

Cost-Effectiveness

FDD systems are considered to have a useful life of 15 years. Therefore we calculated estimates for annual energy savings and the resulting value of savings over 15 years, expressed as a present value. Although the savings returned due to FDD systems are realized over a 15-year life, costs are fixed and must be paid at the time of installation and maintenance. By subtracting the costs from the present value of the cumulative savings, we calculated the net financial benefit of the measure.

We conducted the life cycle cost calculation using the California Energy Commission Time Dependent Valuation (TDV) methodology. Each hour is assigned an estimated price for energy,[5] and the sum of these prices over the life of the measure yields the present dollar value of savings. Life cycle cost is the difference between the TDV $ value for 15 year energy savings and the initial FDD system costs. Cost effectiveness is proved when this difference is positive; in addition, we have reported the benefit/cost ratio as an additional measure of cost effectiveness.

Stakeholder Meetings

All of the main approaches, assumptions and methods of analysis used in this proposal have been presented for review at a number of public Nonresidential HVAC Stakeholder Meetings. At each meeting, the utilities' CASE team invited feedback on the proposed language and analysis thus far, and sent out a summary of what was discussed at the meeting, along with a summary of outstanding questions and issues.

A record of the Stakeholder Meeting presentations, summaries and other supporting documents can be found at www.calcodes.com. Stakeholder meetings were held on the following dates and locations:

- First Nonresidential HVAC Stakeholder Meeting: April 27, 2010, California Lighting Technology Center, Davis, CA.
- FDD Roundtable: July 22, 2010, Western Cooling Efficiency Center, Davis, CA
- Second Nonresidential HVAC Stakeholder Meeting: December 7, 2010, San Ramon Valley Conference Center, San Ramon, CA
- Third Nonresidential HVAC Stakeholder Meeting: March 2011, via webinar.

In addition to the Stakeholder Meetings, a series of other public announcements alerted stakeholders to the proposed changes. These announcements included:

- January 2010: ASHRAE TC 8.11, Orlando, FL
- June 2010: ASHRAE TC 8.11, Albuquerque, NM
- January 2011: ASHRAE TC 8.11, TC 7.5 FDD subcommittee, TC 7.5 main meeting, and 90.1 mechanical subcommittee, Las Vegas, NV

In addition, members of the CASE and PIER teams travelled to Texas in November 2010 and met with stakeholders at Lennox, Trane, and MicroMetl.

Analysis and Results

Fault Detection and Diagnostics (FDD)

FDD is included in 2008 Title 24 as a compliance option. This proposal is to advance FDD as a prescriptive option.

[5] Architectural Energy Corporation. Life Cycle Cost Methodology: 2013 California Building Energy Efficiency Standards. Prepared for the California Energy Commission. November 16, 2010

Results of FDD Research

Numerous HVAC faults were investigated in this study to determine the potential benefit of FDD systems in detecting these faults, including:

1. Air temperature sensor failure/fault
2. Low refrigerant charge
3. High refrigerant charge
4. Compressor short cycling
5. Refrigerant line restrictions/TXV problems
6. Refrigerant line non-condensables
7. Low side HX problem
8. High side HX problem
9. Capacity degradation
10. Efficiency degradation
11. Not economizing when it should
12. Damper not modulating
13. Excess outdoor air

A number of the HVAC faults listed above cannot be directly modeled using the energy simulation tool EnergyPro. In such incidences the failure mode is described by a corresponding EER penalty, which is then modeled in EnergyPro as a lower EER. The values of the EER penalties are from "Evaluation Measurement and Verification of Air Conditioner Quality Maintenance Measures, Mowris, October 2010," which are based on lab testing conducted by Robert Mowris Associates at the Intertek testing facility in Dallas, Texas in October 2010. Descriptions of the investigated failure modes and the modeling assumptions used are included below.

1. **Air temperature sensor failure/fault** - This failure mode is a malfunctioning air temperature sensor, such as the outside air, discharge air, or return air temperature sensor. This could include mis-calibration, complete failure either through damage to the sensor or its wiring, or failure due to disconnected wiring. Calibration issues are more common than sensor failures, thus we modeled this fault as a calibration problem. Temperature sensors are commonly accurate to ± 0.35°F. For a conservative estimate we modeled this fault as ± 3°F accuracy. Calibration errors greater than this and failed sensors will contribute to an even worse energy impact.

2. **Low refrigerant charge: 80% of nominal charge** - Incorrect level of refrigerant charge is represented in this failure mode, designated by a 20% undercharge condition (80% of nominal charge). Refrigerant undercharge may result from improper charging or from a refrigerant leak. While the most common concern about a refrigerant leak is that a greenhouse gas has been released to the atmosphere, a greater impact is caused by the additional CO_2 emissions from fossil fuel power plants due to the lowered efficiency of the HVAC unit.

A typical symptom is low cooling capacity as the evaporator is starved of refrigerant and cannot absorb its rated amount of heat. This causes a high evaporator superheat as the receiver is not getting enough liquid refrigerant from the condenser, which starves the liquid line. The thermal expansion valve (TXV) experiences abnormal pressures and cannot be expected to control evaporator superheat under these conditions. The compressor is pumping only a small amount of refrigerant. Essentially, all the components in the system will be starved of refrigerant.

EnergyPro does not allow a specific model input related to refrigerant charge. Instead, the simulation used -15% EER (a 15% reduction in the rated EER), equivalent to 80% charge, based on laboratory testing results,[6] as shown in Figure 6.

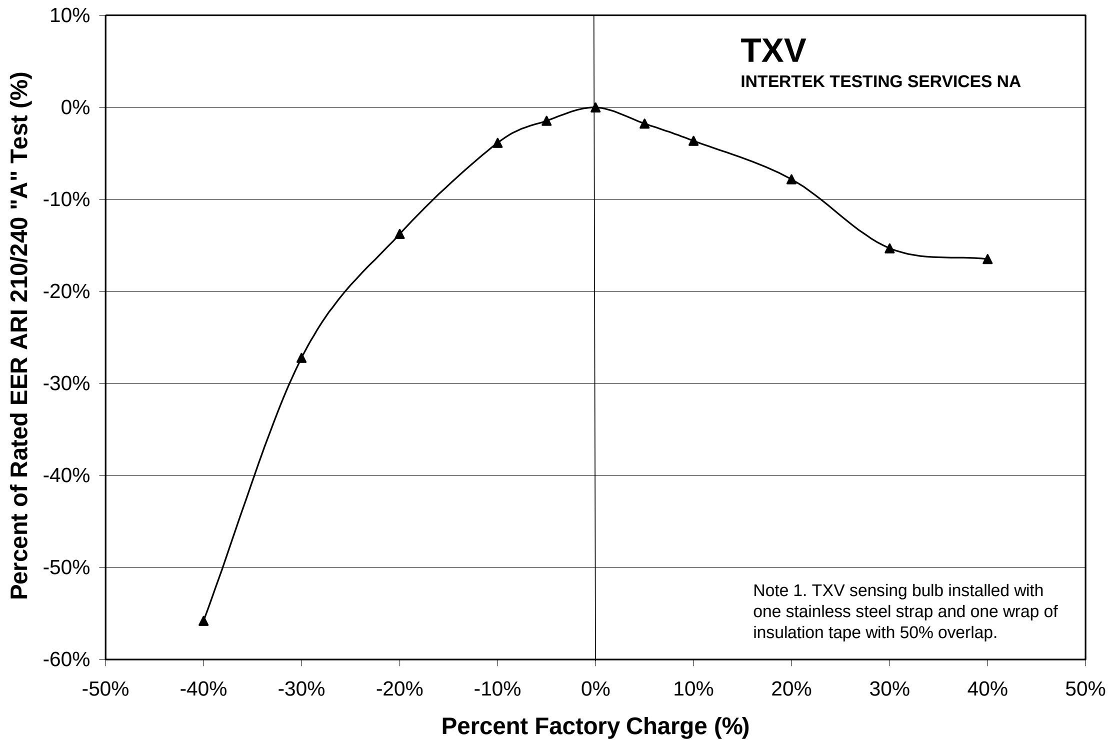

Figure 6 Impact of Refrigerant Charge on EER

3. **High refrigerant charge: 120% of nominal charge** - Incorrect level of refrigerant charge is represented in this failure mode, designated by a 20% overcharge condition (120% of nominal charge). This fault was added to the list after conducting the energy analysis and therefore is not included in the energy analysis. The energy analysis is thus conservative as it does not include this fault.

4. **Compressor short cycling** - Compressor short cycling means that the compressor is enabled again shortly after being stopped for only a brief period of time. Some manufacturers recommend a minimum runtime of 3 minutes and minimum off time of 2 minutes. Thus, short cycling could be considered a runtime shorter than 3 minutes and off time shorter than 2 minutes. Short cycling can originate from many sources, for example coil blockage, equipment oversizing, and a poor thermostat location (e.g. near a supply air diffuser).

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[6] Evaluation Measurement And Verification Of Air Conditioner Quality Maintenance Measures, Mowris, October 2010.

It takes about three minutes of runtime for an RTU to achieve steady state operation and full cooling output. During this time, the unit efficiency is reduced as the refrigerant pressures are established and the evaporator coil cools down. When a unit is short cycling, the startup time becomes a higher fraction of the total runtime. The startup losses thus become a higher fraction of the total cooling output such that the overall efficiency is reduced.

A runtime of 3 minutes and off time of 2 minutes corresponds to a runtime fraction of 60%[7] and an efficiency penalty of 10% according to AEC's Small HVAC System Design Guide.[8] EnergyPro does not allow a specific model input related to compressor short cycling. Instead, the simulation used -10% EER, equivalent to 60% runtime fraction.

Short cycling affects maintenance and repair costs in addition to operating costs. It is one of the most common causes of RTU early maintenance problems and compressor failures. Each time the compressor starts, there is a quick reduction in the crankcase pressure, which results in a portion of the crankcase oil getting pumped out of the compressor. The oil will eventually return to the compressor given sufficient runtime, otherwise the oil will be trapped in the system when the compressor cycles off. With short cycling, the compressor will continue to pump oil from the crankcase, and the entire oil charge can be lost from the crankcase. Without proper lubrication to the compressor, premature failure can result. Compressor short cycling can also cause liquid refrigerant flooding, again threatening premature failure. The compressor starts against nearly full high side discharge pressure, which leads to very high loading of the mechanical components. The electrical components can also be affected, as they are subjected to an unusually high starting current, creating excessive heat and leading to compressor motor overheating.

5. **Refrigerant line restrictions/TXV problems** - Refrigerant line restriction means the refrigerant flowrate is constrained due to a blockage in the refrigerant line. A restriction always causes a pressure drop at the location of the restriction. A suction line restriction will cause low suction pressure and starve the compressor and condenser. This can be caused by restricted and/or dirty suction filters or a bent or crimped refrigerant line from physical damage. A liquid line restriction will cause low pressure and a temperature drop in the liquid line and starve the evaporator, compressor, and condenser. This can be caused by a bent or crimped refrigerant line, a restricted and/or dirty expansion device such as a TXV, a restricted liquid line filter/dryer, or a pipe joint partially filled with solder. In the case of a bent refrigerant line, it acts like an expansion device such that two expansion devices effectively operate in series causing a higher than normal pressure drop. The low evaporator temperature can freeze the evaporator coil and suction line.

EnergyPro does not allow a specific model input related to this fault. Instead, the simulation used -56% EER. This comes from lab test work funded through the Texas A&M Energy Systems Laboratory, which reports that reduced mass flow rate caused by a

[7] 3 min / (3 min + 2 min) = 60%

[8] Integrated Energy Systems: Productivity & Building Science Program, Element 4—Integrated Design of Small Commercial HVAC Systems, Small HVAC Problems and Potential Savings Reports. Submitted to the California Energy Commission. Boulder, CO. Architectural Energy Corporation. 2003. (PIER publication 500-03-082-A-25)

liquid line restriction reduces the EER by 56%.[9] Based on the same lab testing, reduction in suction line decreased the EER by 27%. We choose to model the EER penalty as 56% since there is a much higher probability of damage to the liquid line as the suction line pipes are relatively sturdy.

6. **Refrigerant line non-condensables** - Refrigerant line non-condensables means a type of contaminant has entered the refrigeration lines. This is commonly air, water vapor, or nitrogen. They enter the system through leaks or poor service practices, such as not purging refrigeration hoses while working on a unit or not completely evacuating the system after it has been open for repair. The only fluids in a refrigeration system should be refrigerant and oil. Any other fluids contained within the system can reduce its cooling capacity and lead to premature failure. When air enters a system it will become trapped in the condenser and will not condense. This results in less surface area available for the refrigerant to condense, thus decreasing the capacity of the condenser and increasing its pressure. This causes the compressor to work harder, degrading its efficiency and potentially damaging it by overheating.

EnergyPro does not allow a specific model input related to refrigerant line non-condensables. Instead, the simulation used -8% EER as shown below in Figure 7, which comes from lab testing conducted by Mowris.[10]

Description	Air-Side EER Impact	Total Air-Side Cooling Capacity Btu/hr	Air-Side EER	Total Air Conditioner Power kW	Impact on Air Conditioner Power kW
Baseline total charge 6 lb. 12.2 oz. (228 psig liquid pressure)	NA	31,976	9.69	3.297	NA
Non-Condensable evacuate charge, sweep with Nitrogen, vent to atmospheric pressure (0.3 oz. nitrogen) total charge 6 lb. 12.2 oz. (267 psig liquid pressure)	-7.94%	32,625	9.04	3.608	9.6%

Figure 7 Impact of Non-Condensables on EER

7. **Low side (evaporator) heat exchange problem** - This failure mode is low airflow through the evaporator coil as measured at the unit's supply air discharge. This could be caused by an evaporator coil blockage for example. When the evaporator coil has a reduced airflow, there is reduced heat load on the coil. This can cause the refrigerant in the coil to remain a liquid and not vaporize. The liquid refrigerant will travel past the evaporator coil and reach the compressor, thus flooding and damaging it.

ARI standards are based on airflow rates of 400 cfm/ton. AEC's Small HVAC System

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[9] O'Neal, D., Haberl, J. Monitoring the Performance of a Residential Central Air Conditioner under Degraded Conditions on a Test Bench. May 1992.

[10] Evaluation Measurement And Verification Of Air Conditioner Quality Maintenance Measures, Mowris, October 2010.

Design Guide reports that 39% of units have airflow less than or equal to 300 cfm/ton.[11] Figure 8 shows the corresponding distribution of measured airflow reported by this study.

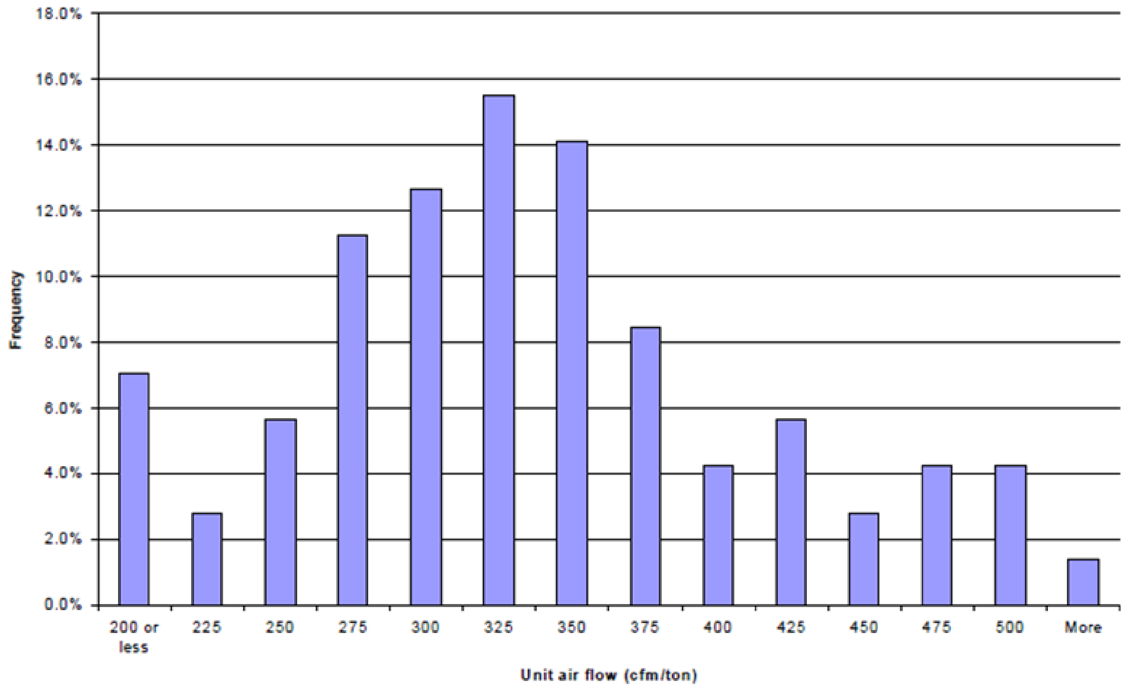

Figure 8 Airflow Distribution in Small Commercial HVAC Units

EnergyPro does not allow a specific model input related to low airflow. Instead, the simulation used -5% EER, equivalent to a low airflow of 300 cfm/ton, from the Mowris study[12], as shown below in Figure 9.

Airflow cfm/ton	EER	EER Impact	Airflow % of Baseline
390.5	9.49	NA	NA
351.0	9.19	-3.16%	-12%
301.5	9.04	-4.74%	-25%
249.6	8.39	-11.59%	-37.5

Figure 9 Impact of Low Airflow on EER

8. **High side (condenser) heat exchange problem** - This failure mode is a 50% condenser coil blockage. In this case, the condenser fails to properly condense the

[11] Integrated Energy Systems: Productivity & Building Science Program, Element 4—Integrated Design of Small Commercial HVAC Systems, Small HVAC Problems and Potential Savings Reports. Submitted to the California Energy Commission. Boulder, CO. Architectural Energy Corporation. 2003. (PIER publication 500-03-082-A-25)

[12] Evaluation Measurement and Verification of Air Conditioner Quality Maintenance Measures, Mowris, October 2010.

refrigerant vapor to a liquid in the middle of the condenser. EnergyPro does not allow a specific model input related to condenser coil blockage. Instead, the simulation used -9% EER, equivalent to 50% condenser coil blockage, from the Mowris study as shown in Figure 10.[13]

Description	Air-Side EER Impact	Total Air-Side Cooling Capacity Btu/hr	Air-Side EER	Total Air Conditioner Power kW	Impact on Air Conditioner Power kW
Baseline	NA	32,335	9.82	3.292	NA
30% Condenser Coil Block	-3.69%	32,136	9.46	3.397	3.19%
50% Condenser Coil Block	-9.07%	31,439	8.93	3.52	6.93%
80% Condenser Coil Block	-32.08%	27,806	6.67	4.168	26.61%

Figure 10 Impact of Condenser Coil Blockage on EER

9. **Capacity degradation** - This fault was added to the list after conducting the energy analysis and therefore is not included in the energy analysis. The energy analysis is thus conservative as it does not include this fault.

10. **Efficiency degradation** - This fault was added to the list after conducting the energy analysis and therefore is not included in the energy analysis. The energy analysis is thus conservative as it does not include this fault.

11. **Not economizing when it should** – This was represented as economizer high limit setpoint is 55˚F instead of 75˚F. An economizer is equipped with a changeover (high limit) control that returns the outside air damper to a minimum ventilation position when the outside air is too warm to provide cooling. Economizers should use a 75˚F high limit setpoint in climate zones 1, 2, 3, 5, 11, 13, 14, 15 and 16, per Title 24 Table 144-C as referenced in Section 144(e)3. This failure mode is easily modeled by changing the high limit setpoint from 75˚F (base case) to the failure mode of 55˚F. The 55˚F setting instead of the 75˚F setting results in missed opportunities for free cooling between the range of 55˚F and 75˚F, thus losing a large number of economizer hours and energy savings potential.

The baseline economizer control is a snap disk, which is a round silver temperature sensor that typically has a setpoint of around 55°F; an adjustable setting might be up to 60°F, but not higher with a single stage thermostat. This type of sensor severely limits economizer operation.

Many economizer controllers have the high limit or change over control listed as A B C D rather than a particular temperature. The high limit settings for these labels are shown in Figure 11. The proper temperature high limit to use is the cut-out position of the high limit (or upper end of the control hysteresis) based on the controller and sensor combination. Note that the screw dial can be set between letters.

[13] Ibid.

High Limit Setting	Controller with dry-bulb sensor	Economizer Controller with dip switch settings (switch 1-Switch 2)
D	55°F	55°F (OFF-ON)
D-C	62°F	60°F (OFF-OFF factory)
C	68°F	65°F (ON-OFF)
C-B (desired setting)	75°F	single sensor high limit cannot be set above 65°F high limit
B	82°F	
A	95°F	

Figure 11 Economizer High Limit Settings for Two Controllers

12. **Damper not modulating** – This was represented as economizer stuck closed. When the economizer damper is stuck closed the unit fails to provide any ventilation and is a missed opportunity for free cooling, thus causing an energy penalty during periods when free cooling is available. This was modeled as “no economizer” in EnergyPro.

13. **Excess outdoor air** – This was represented as economizer stuck 100% open. When the economizer damper is stuck open the unit provides an excessive level of ventilation, usually much higher than is needed for design minimum ventilation. It causes an energy penalty during periods when the economizer should not be enabled, that is, during heating and when outdoor conditions are higher than the economizer high limit setpoint. During heating mode the stuck open economizer will bring in very cold air and the gas usage will increase significantly. This was modeled as 100% outside air in EnergyPro.

Energy simulation

This analysis used a special version of EnergyPro 5.1 that has been configured to use the 2013 weather files developed for the 16 different climate zones by Joe Huang with Whitebox Technologies for the CEC. These climate zone files are intended to serve as the reference data for 2013 code analysis. The version of EnergyPro was configured identically to the version certified for use with the 2008 Title 24 standards, outside of the weather file change.

A series of prototype buildings were developed that were based upon actual project designs in terms of building configuration. Thus for the large retail example, an actual big box retail store was used so that we would have a realistic approximation of glazing area, number of stories and building geometry. In the case of each prototype, each building was configured with Title 24 standard assumptions for insulation levels and glazing type and a standard lighting power density was used. Since the Alternative Calculation Method (ACM) manual rules are applied automatically by EnergyPro during the analysis, assumptions like occupant densities, ventilation rates, etc are all automatically set to the standard values listed in the ACM manual. The HVAC systems in each case were configured as standard Packaged Rooftop Gas Heat/Electric Air Conditioning systems with minimum efficiencies as specified in either Title 24 or Title 20, depending upon system size. Since part of the study includes looking at the effectiveness of economizers, each system was configured with an economizer, even though the requirements in section 144 of the code may not require it be installed.

Once each prototype was developed, a series of runs was performed in the 16 different climate zones. Each run looked at the implications of the degradation of certain portions of the HVAC system. Features such as an economizer that is stuck open, systems that have short cycling, incorrect thermostat signals, etc were analyzed and compared to the basecase that assumes a perfectly functioning system.

For efficiency, simulations are needed only at three EER values to define a curve. The resulting energy savings and TDV savings are directly proportional to the EER penalty. Thus, any additional failure modes described by an EER penalty can be derived from these three models via interpolation. Any failure modes not described by an EER penalty will of course still require a unique simulation. This is summarized below in Figure 12. An example interpolation is shown in Figure 13 and Figure 14 for a 5-ton RTU, small office, in climate zone 12.

Failure mode	EER penalty	Energy savings calculation method
Low airflow: 300 cfm/ton	5%	Simulation
Low side HX problem incl. low airflow (50% evaporator coil blockage)	5%	Simulation
Refrigerant charge: 80% of nominal charge	15%	Simulation
Performance degradation: 30% cond. block, 300 cfm/ton, -10% charge	21%	Simulation
Refrigerant line non-condensables	8%	Interpolation
High side HX problem (50% condenser coil blockage)	9%	Interpolation
Compressor short cycling	10%	Interpolation
Refrigerant line restrictions/TXV problems	56%	Extrapolation

Figure 12 FDD Failure Modes by EER Penalty

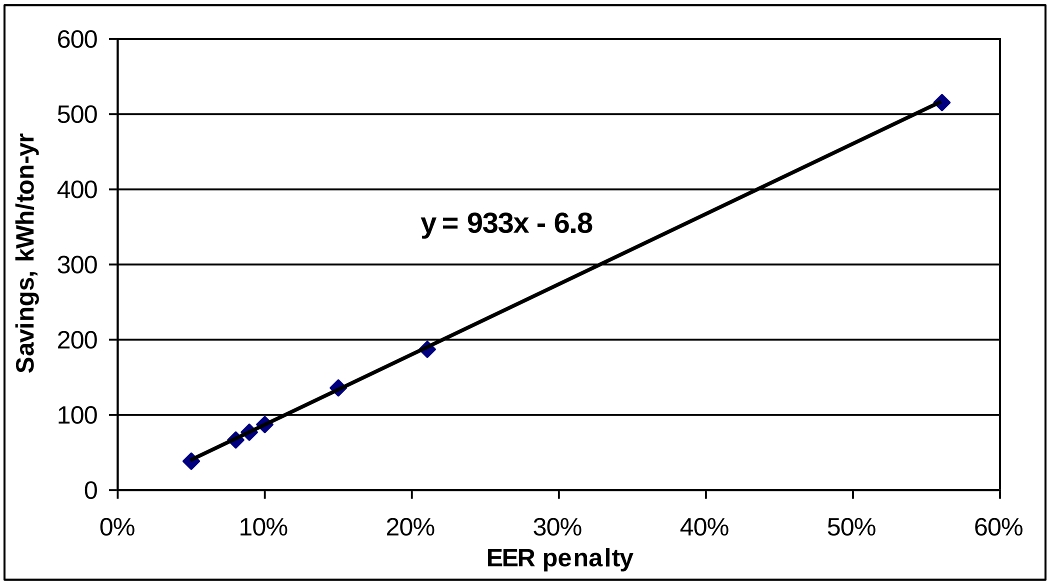

Figure 13 Electric Savings as Function of EER Penalty, 5-ton RTU, Small Office, CTZ 12

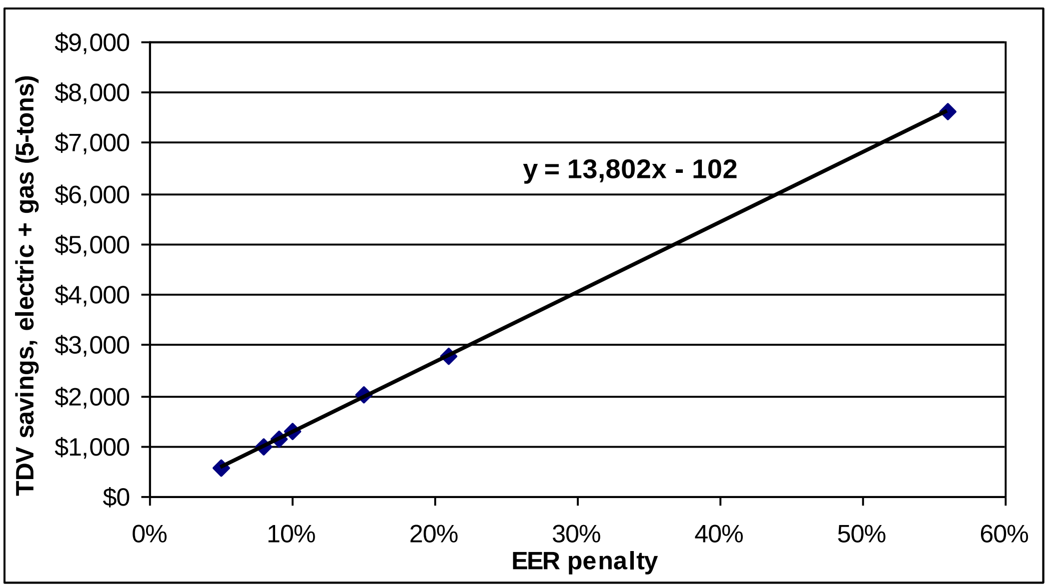

Figure 14 TDV Energy Savings as Function of EER Penalty, 5-ton RTU, Small Office, CTZ 12

Probability Analysis

Thus far, the energy savings described above assumes a 100% failure rate, a 100% chance of the FDD system detecting the fault, and a 0% chance the fault would be detected without an FDD system. In reality, not all units will experience all these faults, the chance of the FDD system detecting the fault is less than 100%, and the chance the fault would be detected without an FDD system is greater than 0%. It is necessary to account for this to avoid overestimating the potential energy savings from implementing an FDD system. This section describes the methodology used to estimate the failure rate and the probability of detecting the faults with and without an FDD system. This method does not account for any interactive effects if multiple failures are encountered, but provides a reasonable distribution of outcome for each test.

This analysis relies on fault incidence. Incidence is the frequency at which a fault occurs in a specific time period or the rate of occurrence of new cases of a fault in the population of interest (e.g., all RTUs in California).

$$Incidence = \frac{\text{Number of units in a population developing the fault in a time interval (e.g., a year)}}{\text{Total number of units in the population during the time interval of measurement}}$$

This is not to be confused with prevalence, which is the number of cases that exist in the population of interest at a specific point in time. For example, the number of economizer faults in all packaged units in the U.S. presently.

$$Prevalence = \frac{\text{Number of units in the population with the fault at a specific time}}{\text{Total number of units in the population at a specific time}}$$

For example, with regard to the refrigerant line restriction fault, it is reported as a 60% probability that a filter/dryer restriction fault will occur once during the equipment lifetime.[14] Adding the probability of damage to the liquid line and other restrictions yields an estimated 75% probability for a refrigerant line restriction/TXV fault during the equipment lifetime. Considering the average air conditioner lifespan of 18.4 years as reported by the DOE[15], the annual incidence is 75% ÷ 18.4 = 4.1%. This means 4.1% of RTUs will develop a refrigerant line restriction fault each year. Considering the 15 year nonresidential analysis period, 62% (4.1% x 15) of RTUs will develop a refrigerant line restriction fault within 15 years.

Figure 15 and Figure 16 show the number of faults identified by the AirCare Plus (ACP) program as a function of the unit's vintage. The slope of the linear trendlines indicate the number of new faults per year. This is presented for the first five years of a unit's lifetime. In other words, this dataset contains the newest units in the entire ACP dataset. This allows for new equipment design and factory assembly and quality control processes that may affect the incidence of faults, while avoiding most obsolete designs and processes. To convert this data to incidence, these number of new faults per year are simply divided by the total number of units in the population during the time interval of measurement (units tested/yr). Figure 17 summarizes the results.

[14] Automated Fault Detection and Diagnosis of Rooftop Air Conditioners for California, Deliverables 2.1.6a & 2.1.6b. Braun, Li, August 2003

[15] US DOE, Technical Support Document: Energy Efficiency Standards for Consumer Products, May 2002.

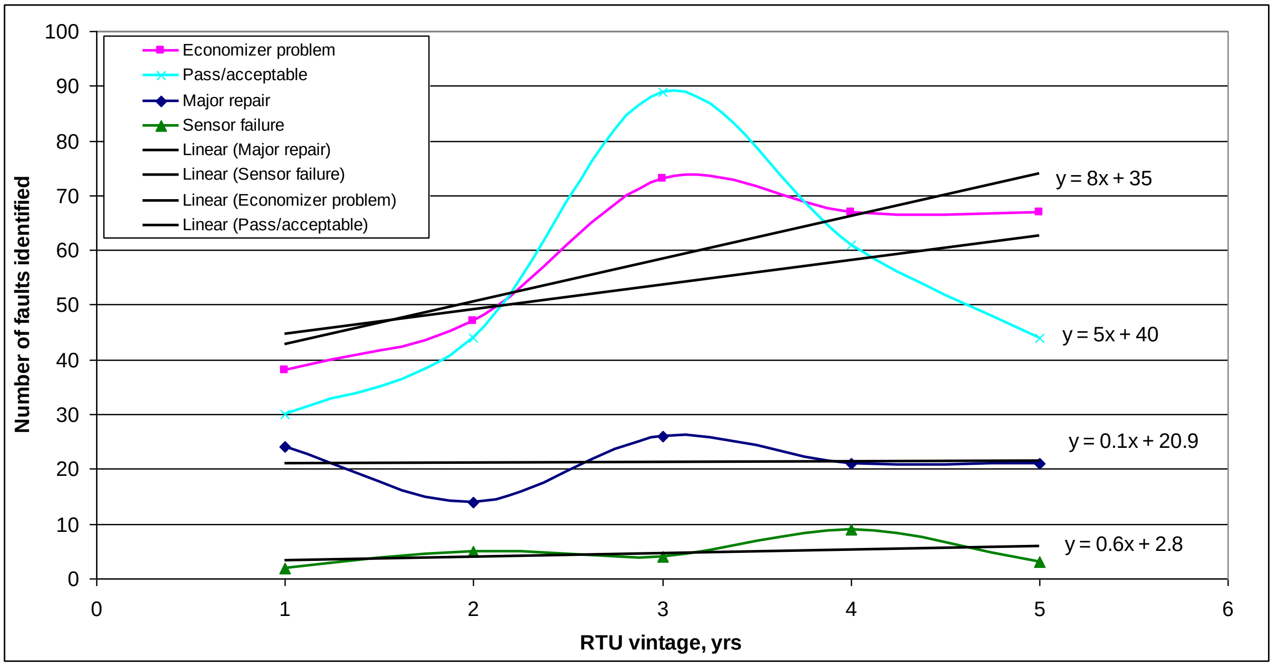

Figure 15 Faults by RTU Vintage: Economizer and Sensor Faults

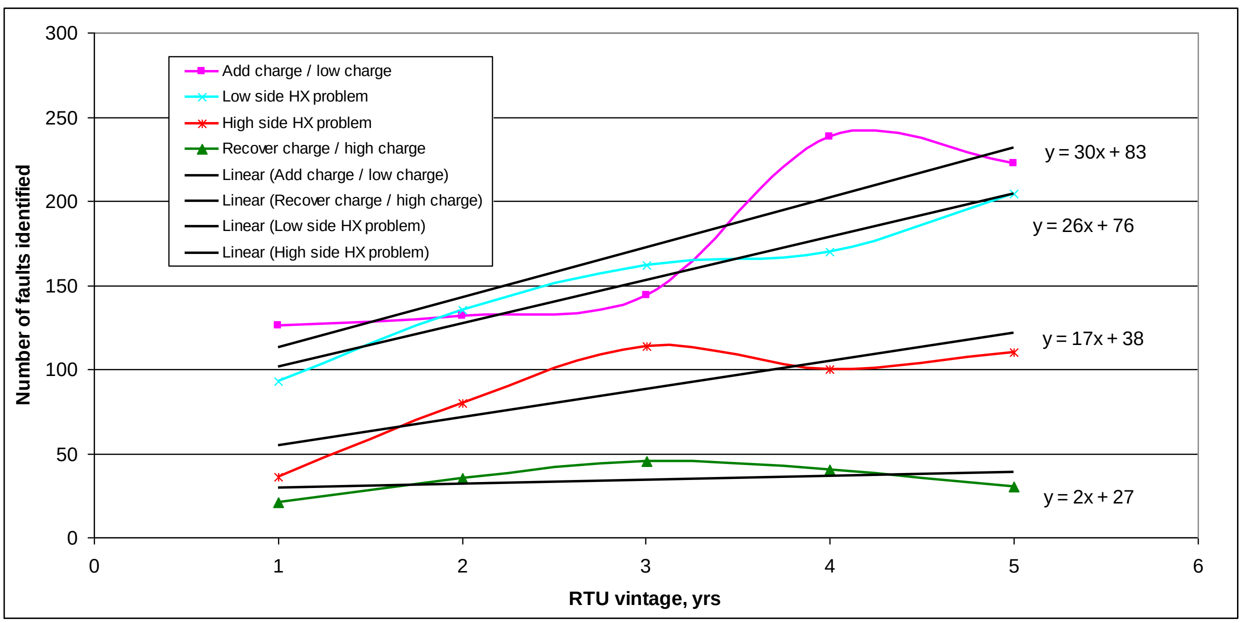

Figure 16 Faults by RTU Vintage: Refrigerant and Heat Exchange Faults

	Pass/ acceptable	Major repair	Add charge / low charge	Recover charge / high charge	Low side HX problem	High side HX problem	Economizer problem	Sensor failure
Slope (faults/yr)	5	0.1	30	2	26	17	8	0.6
Units tested/yr	527	527	527	527	527	527	251	527
Incidence	0.9%	0.0%	5.7%	0.4%	4.9%	3.2%	3.2%	0.1%
x 15 yrs analysis period	14%	0%	85%	6%	74%	48%	48%	2%

Figure 17 Summary of Fault Incidence Analysis

This analysis still assumes a 100% chance of the FDD system detecting the fault, and a 0% chance the fault would be detected without an FDD system. In reality, not all units will experience all these faults. The chance of the FDD system detecting the fault is closer to 75%. The chance the fault would be detected without an FDD system varies depending on typical service and if the fault impacts comfort conditions.

The following fault is quite likely detected by the economizer acceptance test or through regular service such that the fault is 75% likely to be detected:

- Economizer high-limit setpoint 55˚F instead of 75˚F

The following fault is likely detected through regular service and/or impact comfort conditions such that the fault is 50% likely to be detected:

- Refrigerant charge: 80% of nominal charge

The following list of faults are less likely detected through regular service and do not impact comfort conditions such that the fault is 25% likely to be detected.

- OAT sensor malfunction
- Compressor short cycling
- Refrigerant line restrictions/TXV problems
- Refrigerant line non-condensables
- Low side HX problem incl. low airflow (50% evaporator coil blockage)
- High side HX problem (50% condenser coil blockage)
- Economizer stuck closed
- Economizer stuck open

Figure 18 summarizes the results of the probability analysis. The FDD benefit is the difference between the probability of detecting the fault with FDD and the probability of detecting the fault without FDD.

Failure Mode	Fault incidence (over 15 years)	Prob. of detecting the fault w/FDD	Prob. of detecting the fault w/o FDD	Fault incidence x FDD benefit
Air temperature sensor malfunction	2%	75%	25%	1%
Refrigerant charge: 80% of nominal charge (-15% EER)	85%	75%	50%	21%
Compressor short cycling	30%	75%	25%	15%
Refrigerant line restrictions/TXV problems	62%	75%	25%	31%
Refrigerant line non-condensibles (-8% EER)	50%	75%	25%	25%
Low side HX problem incl. low airflow (50% evaporator coil blockage; -5% EER)	74%	75%	25%	37%
High side HX problem (50% condenser coil blockage; -9% EER)	48%	75%	25%	24%
Not economizing when it should (high-limit setpoint 55F instead of 75F)	30%	75%	75%	0%
Damper not modulating	24%	75%	25%	12%
Excess outdoor air	24%	75%	25%	12%

Figure 18 Summary of FDD Probability Analysis

Energy Savings

In the end, it was decided to shorten this list of faults. This proposal and thus the energy savings consist of only a subset of the analyzed faults. In particular, it includes only the faults that both the third party FDD systems and the HVAC OEMs can currently detect as of April 2011. The FDD system shall detect the following faults:

- Air temperature sensor failure/fault
- Low refrigerant charge
- Not economizing when it should
- Economizing when it should not
- Damper not modulating
- Excess outside air

Figure 19 shows the annual energy savings for each of these failure modes averaged over the EUL of 15 years. These savings values represent the weighted average by new construction estimate for the next 15 years[16] across all climate zones and simulated building types. These values were then multiplied by the fault incidence x FDD benefit number (over 15 years) to determine the FDD savings benefit by failure mode.

Failure Mode	Avg. kWh/ton-yr savings over EUL	Avg. kW/ton savings over EUL	Avg. therms/ton-yr savings over EUL	fault incidence x FDD benefit number	Avg. kWh/ton-yr savings over EUL	Avg. kW/ton savings over EUL	Avg. therms/ton-yr savings over EUL	$1.86 PV /kWh/ton	$14.59 PV /therm/ton	PV$ total/ton
Air temperature sensor failure/fault	9.5	0.0	0.0	1%	0.1	0.0	0.0	$0.18	$0.00	$0.18
Low refrigerant charge	133	0.1	0.0	21%	28	0.0	0.0	$52	$0	$52
Not economizing when it should	448	0.0	0.0	0%	0.0	0.0	0.0	$0	$0	$0
Economizing when it should not	Did not model this failure mode									
Damper not modulating	535	0.0	0.0	12%	64	0.0	0.0	$119	$0	$119
Excess outside air	136	0.3	71	12%	16	0.0	8.5	$30	$125	$155
Total	***1,261***	***0.4***	***71***	***46%***	***109***	***0.1***	***8.5***	***$202***	***$125***	***$326***

Figure 19 Savings by Failure Mode

Linear regression is used per climate zone and building type to determine the savings associated with the failure modes described by the EER penalty that were not simulated. The results of the probability analysis are applied to the energy savings results per climate zone and building type by multiplying the savings for each failure mode by the last column in Figure 18 (Fault incidence x FDD benefit). This yields the benefit of FDD considering the fault incidence and the probability of detecting the faults with and without an FDD system. These savings are then summed by climate zone and building type across all failure modes.

The Present Value (PV) energy savings over the effective useful life (EUL) of 15 years is $1,467 per RTU for a 54,000 Btu/h unit. The annual energy and gas savings is 490 kWh and 38 therms per RTU for a 54,000 Btu/h unit. The first year and 15-year statewide savings realized by implementing this measure are presented in Figure 20. To estimate statewide electricity savings, the savings per building type and climate zone are divided by the building square footage and multiplied by the new construction estimate for the year 2014[16] for the given climate zone and building type. These values are then summed over all the climate zones to yield the statewide savings. The only difference in the 15 year electricity savings calculation is the new construction estimates for the years 2014 to 2020 are used. The 2020 estimate was multiplied by 9 to estimate savings beyond the year 2020 and result in 15 years total.

[16] Heschong Mahone Group, Inc. Nonresidential Construction Forecast by Climate Zone. Version 7.

Statewide Savings	Electricity Savings (kWh)	TDV Total $	Demand Savings (kW)
1st Year Savings	2,104,909	$676,584	1,486
15 Year Savings	30,928,493	$8,051,354	22,798

Figure 20 FDD Statewide Savings

Another view of statewide savings by building type and climate zone is shown in Figure 21.
The overall statewide average (weighted by new construction forecast) annual savings is 12% for both the kWh and the kW savings.

	FDD Annual Energy Savings as % of Annual RTU Consumption															
California Climate Zone:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Fast Food	16%	16%	16%	16%	16%	16%	16%	15%	15%	15%	13%	13%	13%	13%	13%	9%
Grocery	17%	17%	17%	17%	15%	15%	15%	16%	16%	16%	15%	15%	15%	16%	16%	12%
Large Office	9%	9%	9%	9%	9%	9%	9%	10%	10%	10%	9%	9%	9%	9%	9%	6%
Large Retail	13%	13%	13%	13%	11%	11%	11%	11%	11%	11%	10%	10%	10%	9%	9%	8%
School	15%	15%	15%	15%	15%	15%	15%	17%	17%	17%	14%	14%	14%	14%	14%	10%
Small Office	9%	9%	9%	9%	10%	10%	10%	11%	11%	11%	10%	10%	10%	10%	10%	7%
Small Retail	18%	18%	18%	18%	17%	17%	17%	14%	14%	14%	12%	12%	12%	11%	11%	10%

Figure 21 FDD Annual Savings as % of Annual RTU Consumption

Maintenance Savings

Braun and Li report, "A technician will only detect and diagnose severe and obvious faults. In the absence of preventive maintenance, technicians would typically be called to perform emergency service when an air conditioner is not working or is unable to maintain comfort. Even if preventive maintenance is performed, the procedures only involve routine checks that can only detect severe and obvious faults. If an automated FDD system were applied, most (e.g, 75%) of the planned preventive maintenance inspection fees would be saved. One coil cleaning service can be saved per year through automated FDD."[17]

Li and Braun claim, "Automated FDD reduces service costs due to reduced preventive maintenance inspections, fault prevention, lower-cost FDD, better scheduling of multiple service activities, and shifting service to low season." A significant part of a service cost is the base visit fee. Through better scheduling of multiple service activities, the base visit fee can be shared across multiple faults on a single cooling system or multiple cooling systems of a site. Some combinations of services also allow cost savings. For example, any combination of faults that require recovering the refrigerant will prove a cost savings if addressed during a single visit. They conclude that $30/kW can be saved

[17] Braun, James, and Haorong Li. 2003. Automated Fault Detection and Diagnosis of Rooftop Air Conditioners for California, Deliverables 2.1.6a & 2.1.6b.

annually on the service costs.[18] To maintain a conservative analysis, we used 50% of this value, or $15/kW ($16/ton) annual maintenance cost savings for this measure. This yields a present value maintenance cost savings of $179/kW ($195/ton) at 1.09 kW/ton or $878 for a 54 kBtu/h unit.

Measure Cost

For our measure cost analysis we used information provided by Heinemeier, et al., who report, "Processing of diagnostic algorithms can take place in the onboard controller, on an installed PC, or remotely. Even when a PC or remote computer is used, there may still be a need for on-site signal processing to reduce the data and pre-process them. In most cases, these processing platforms do not contribute significantly to the cost. For some methods, however, it will be significant.

- High cost: An approach that uses an EMS platform for processing
- Moderate cost: An approach that that can be accomplished by an embedded controller
- Low cost: An approach that can be accomplished only with use of an added PC or processor

The defined scope for this program is remote diagnostics, so all approaches considered here will require remote communications. For remote diagnostics, communications hardware and access are required. This can be accomplished by tying into the building's Energy Management System, or installing a dedicated modem and phone line. It is often possible to use a gateway to allow the diagnostic module to piggy-back on the building's communications infrastructure to reach the internet."[19]

The cost of the FDSI Sentinel and PNNL's Smart Monitoring and Diagnostic System (SMDS) FDD systems are in the range of $250 to $400 (OEM cost) or $1600 (building owner installed cost after factor of 4 mark-up). The cost of the Sensus MI system is $5,000 to $15,000 per building. The nature of this solution is such that this tool is best implemented at locations with many RTUs such as big box retail. Thus the cost per RTU is less than that of the FDSI Sentinel and the SMDS. For conservativeness, the highest cost of this suite of tools is used for the cost analysis, which is $1600/RTU. This cost includes many more faults than the list of five faults proposed here, thus continuing the list of conservative assumptions. Another reason why this is a conservative assumption is because the installed cost for the OEM solution is much less than $1600.

Sensus MI and FDSI Sentinel can detect all the faults on our proposed list. SMDS can detect all the faults except low airflow, refrigerant charge, and insufficient capacity.

With regard to PNNL's SMDS tool, "Battelle Pacific Northwest Division in collaboration with NorthWrite Inc. has developed a tool for continuously monitoring the condition and performance of packaged air conditioners and heat pumps. The Smart Monitoring and

[18] Li, Haorong, and James Braun. 2007. Economic Evaluation of Benefits Associated with Automated Fault Detection and Diagnosis in Rooftop Air Conditioners. *ASHRAE Transactions* 113(2).

[19] Heinemeier, Kristin, (WCEC), and Julien Bec (UCD). 2010. Fault Detection And Diagnostics, Moving The Market And Informing Standards In California: FDD Prioritization. California Energy Commission.

Diagnostic System (SMDS) is mounted in a small box installed on the side of each packaged air conditioner or heat pump and provides continuous remote monitoring and diagnostics for the unit. It requires the following components:

- Temperature sensor
- Data processing module
- Communication module (required for any FDD)

The SMDS works by constantly collecting data from sensors installed on the equipment to measure its performance and detect and diagnose problems with its operation. The unit then sends the results wirelessly, directly from each packaged unit to a network operations center, where the data are stored securely and information on the condition of each packaged unit is made available on the internet. The SMDS can be installed on new or existing packaged air conditioners and heat pumps."[20]

Cost Effectiveness/LCCA

The total incremental cost is the sum of the incremental installed cost of $1,600 and the PV maintenance cost of - $878 for a total incremental cost of $722. As shown in Figure 22, the measure is cost effective for the proposed size threshold of 54 kBtu/h unit and larger.

Incremental Installed Cost	$1,600
Incremental Annual Maintenance, 54 kBtuh	($74)
PV of Annual Maintenance, 54 kBtuh	($878)
Total Incremental Cost, 54 kBtuh	$722
PV of Energy Savings, 54 kBtuh	$1,467
Lifecycle cost savings	$745
Benefit/Cost Ratio	2.0

Figure 22 FDD: Lifecycle Cost Results

[20] Ibid.

APPENDIX C: TITLE 24 FDD STANDARD: DEVELOPMENT METHOD AND FINAL LANGUAGE

Public Interest Energy Research (PIER) Program
PROJECT REPORT

Fault Detection and Diagnostics: Moving the Market and Informing Standards in California

A3: Title 24 FDD Standard for Rooftop Units

WESTERN COOLING EFFICIENCY CENTER

A Report of the Western Cooling Efficiency Center

RESEARCH • INNOVATION • PARTNERSHIP

new buildings institute

Prepared for: California Energy Commission
Prepared by: Western Cooling Efficiency Center and New Buildings Institute

MARCH, 2011
CEC-500-08-049

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DEVELOPMENT OF A FDD STANDARD FOR ROOFTOP UNITS IN CA TITLE 24

In the third Phase, WCEC and NBI, in conjunction with PECI and HMG of the Codes and Standards Enhancement (CASE) project, developed a draft specification for new requirements for FDD in Rooftop Units. We held an industry roundtable to present the draft to a set of industry actors, and obtain their feedback.

Remote and automated Fault Detection and Diagnostic (FDD) tools have the potential to save considerable energy in California fleet of existing commercial rooftop air conditioning units (RTUs). The market for these systems has not yet materialized, however. Tools have been available for larger systems for some time, although even these have not enjoyed a significant market share. In RTUs, there are fewer tools available, and little to no market share.

Since RTUs cool over 70% of the commercial square footage in California, they are a significant source of energy consumption and peak demand. Under the best of circumstances, RTUs are not as efficient as larger built up systems. However, in reality, they are even less efficient. Many market failures have led to a lack of quality in installation and maintenance of these units, and their performance is suffering. Most RTUs have some sort of fault that is increasing their energy use. If these faults could be found and addressed, then energy savings could be realized.

In the master research report – to which this is an Appendix - "Rooftop HVAC Fault Detection and Diagnostics: *New Technologies and Standards for Energy Reduction*," we identified nine different potential approaches, depending on the type of data collected (air side, refrigerant side, or electrical) and the type of model used for comparison with measurements (first principles, qualitative, history). We also identified the specific criteria that must be met to have a measure that is appropriate for inclusion in Title 24. These criteria included significant energy savings, cost effectiveness, prevalence of the fault being detected, probability that the fault will be fixed, reliability of detection, deployability, and other maintenance benefits.

The faults that can be detected by various FDD tools include efficiency degradation, low charge, coil fouling, filter dirty, insufficient capacity, excessive operating time, incorrect control sequence, lack of ventilation, insufficient economizing, unnecessary outdoor sir, failed sensor, control problems, failed compressor, stuck damper, slipping belt, leaking valves, short cycling, unit not operational. The tools that are available are shown below:

Tool Name	Status	Data	Model	Developer
FDSI Insight V.1	Available	Refrigerant	Quantitative	Field Diagnostics, Inc
Sensus MI	Available	Air	Qualitative	University of Nebraska
ClimaCheck	Available	Refrigerant	Quantitative	ClimaCheck Inc.
SMDS	Pilot	Air	Qualitative	Pacific Northwest National Lab
NILM	Pilot	Power	Qualitative	Massachusetts Institute of Technology
Low Cost NILM	Pilot	Power	Timeseries	Massachusetts Institute of Technology
Sentinel/Insight	Beta	Refrigerant	Quantitative	Field Diagnostics, Inc
Virtjoule	Developing	Power	Timeseries	Virtjoule Inc.
Low Cost SMDS	Developing	Air-Power	Timeseries	Pacific Northwest National Lab

Process to Develop the Draft FDD Standard for Rooftop Units

In order to develop the initial draft specification for a RTU FDD standard, we undertook several tasks. We reviewed the current optional requirements for FDD in Title 24 (2008) to determine the level of specificity that the new requirements might entail. We developed a short summary of the existing standard that includes all of the requirements contained in the Standard, the ACM, the User's Manual, and the Acceptance Test Forms. We revised this summary to include the new requirements we felt might be included in a new standard. The document shown in Attachment 1 in this report is the summary of the initial draft Title 24 FDD proposal for FDD in RTUs. ***(NOTE that this Proposal was updated Feb 2011 after subsequent stakeholder input and then again to become the final submittal and approved version for Title 24).***

Industry Roundtable

An Industry Roundtable was held at the Western Cooling Efficiency Center, UC/Davis on July 22, 2010. The attendees are shown in Attachment 2.

Summary of Discussion

The discussion among participants both in person and those remotely was wide and deep, limiting this report to a high level summary. What follows are key takeaways and issues identified to follow up on for both the PIER and CASE team researchers. We will be contacting individual participants for further discussion about comments made at the Roundtable and those received pre- and post-roundtable. We very much appreciated the positive tone of the meeting. This is a complex topic, as all of you all understand. There are different needs for different markets that have to be accounted for and balanced in setting standards. For example, Walmart needs an approach to manage the 25 million HVAC alarms generated company-wide in 2009. The company needs intelligence that manages and reduces alarms, not necessarily additional sensors and algorithms that add to them. Compare this with the owner of a suburban 10,000sf, two-story office building with a handful of RTUs, who would benefit from basic FDD functionality in the RTUs such as monitoring airflow, economizer operation, sensor malfunction, refrigeration charge status and not a whole lot more.

The tenor of the meeting was very positive. Overall, the researchers got the message to:

- Proceed with the potential for a 2011 Title 24 Prescriptive Measure
- Provide substantiation of:
    - FDD energy savings benefits and persistence
    - FDD product availability, in the market or on the way
    - FDD product costs including communications gateway
    - Fault priorities/prevalence
- Take the RTU FDD discussion national including the manufacturers and ASHRAE 90.1

In summary, participants collectively took a useful step on the path toward increasing, maintaining and controlling the energy efficiency of RTUs through FDD methods as a component of enhanced performance monitoring and performance measurement.

Key Takeaways (summarized as offered at the end of the meeting)

a. As an alternative first step, explore an approach to first capture the data, perhaps in the T-stat, before analysis methods are standardized. How long to store data? Who collects/analyzes? How does it become actionable information?

b. Move toward a 2011 T24 Prescriptive Measure submission; it's possible, but challenging.

c. It was noted by the manufacturers that "the hardware is the easy part," and by the FDD tool developers that "we can't manufacture this in a big way tomorrow." Partnering may be required to move this technology into the market quickly.

d. Initiate an 'FDD Challenge' similar to the idea of the Western Cooling Challenge, to pull the products into the market more quickly and at the same time, work to condition the market for the products. This might happen in cooperation with the Retailer Energy Alliance that US DOE supports.

e. Assess both a 'performance degradation factor' and a "performance index" as a potential overall performance monitoring/fault condition indicator to the RTU owner/manager/servicing contractor. What is the threshold definition for detecting faults that drive the degradation factor? How low is too low?

f. Further prioritize the faults in severity and frequency. There are other performance issues that are not on the list in the Strawman.

g. It's a complicated picture with the manufacturers, entrepreneurs, customers, and utilities all having separate driving interests.

h. Engage the utilities Emerging Technology programs for proof-of-product and then potentially tap into utility incentive programs and then into Title 24.

i. FDD is an enabling technology. While we can't make anyone use the information that is or will be available from this type of monitoring, the fact that the information exists drives the potential for market understanding and enables action. Some factor must be developed to account for this indirect benefit.

j. Sensor accuracy/persistence is unquestionably an issue and is being addressed by ASHRAE. We need to get up to speed on this activity.

k. Pick the top four faults in the Strawman along with Performance Degradation indicator and that's enough.

l. Take this discussion national to bring in additional manufacturers of FDD products. Need the FDD business case and volume business to catch industry attention.

m. RTUs can be split into those with electro-mechanical controls or with microprocessor controls. This dictates what is possible with sensing and communications.

n. Transmit the performance data/alarms/FDD off the roof for remote viewing. Webenabled is a real option.

o. Title 24 standard should not be too prescriptive. Try to specify performance objectives within the prescriptive measure. This can drive new technology solutions.

p. FDD should be integrated with Quality Installation practice

Quotable Quotes

q. “The California Reach Code is not a dumping ground for unsupported measures.”

r. “FDD needs to be developed into an iPhone or iPad app.”

s. “Innovation comes into the market at the speed of profits.”

Next Steps toward Final Title 24 FDD Proposal

The next steps in this research project included:

- *Quantify the expected energy savings and costs of systems*. By conducting a survey and analysis of system costs, and simulating the savings attributable to FDD, we can estimate the cost effectiveness in a typical building. This modeling may also be used to determine savings from implementing FDD in a specific RTU, for compliance purposes. This work will be done in parallel with the next step, and will be complete in the first quarter of 2011.
- *Discuss with industry stakeholders to get additional feedback on the draft requirements.* The draft standard will be disseminated widely and feedback from a range of stakeholders will be taken into account in developing a Code Change Proposal. This will be done in parallel with the first step and will be complete by the end of the first quarter of 2011.
- *Develop a formal Code Proposal*. Once all possible input has been obtained on the draft standard, a formal Code Change Proposal will be developed. This will be done in conjunction with Portland Energy Conservation, Inc. The role of the CEC team will be defining requirements and reviewing draft proposals. This will be completed by April of 2011, or whenever the deadline is for submission of proposals.
- *Follow the CEC review process*. The interviews and analysis conducted by the CEC team are part of the due-diligence that is required for any Code Change proposal. This process also includes formal stakeholder workshops and an open comment period. The CEC team will participate in these workshops and responding to questions, as needed and appropriate. This is expected to occur in April of 2011.

Summary of Final Title 24 Language

A major shift is underway nationally, with manufacturers making design decisions to include more fault alarms across equipment lines. There is an important distinction that has to be made regarding the phrase ‘fault detection and diagnostics (FDD).’ While a fault might be detected and an alarm signal sent into the building to a digital thermostat/control, a building energy management system, or to a remote location such as a maintenance contractor, the diagnosis of the cause of the alarm is not as clear-cut. Some faults may have multiple causes. For example, a low refrigeration pressure alarm could be the result of low refrigerant charge, dirty filters, evaporator fan turning backwards, loose or broken fan belt, plugged filter drier, faulty transducer, excessively cold return air, or stuck open economizer when the ambient temperature is low. The key is the alarm and providing notification to appropriate personnel either maintenance staff on site or to the HVAC maintenance contractor. For most RTU's the alarm would be provided on site. Typically, only buildings with EMS and remote communications capability are capable of sending alarm notifications off site.

Work sponsored in California by the Energy Commission and utilities[21] have **led to a mandatory measure approved for the 2013 revision of the Title 24 commercial building energy standards**.

The measure will require that all air-cooled package, split system, and VRF units with economizers, at sizes 4.5 tons and above, have a minimum set of fault detection alarms aimed primarily at the economizer. As important, is the requirement that the fault notification must be communicated off the roof. The fault reporting mechanism and destination are not prescribed. If adopted, this first FDD code requirement may have an impact on the national RTU market when the revised Title 24 standard comes into force in January 2014.

The faults to be reported include:

- Sensor failure or fault
- Not economizing when it should
- Economizing when it should not
- Damper not modulating
- Excessive air flow

The limits to applying the new standard across the fleet of RTUs comes from the control design of the unit. Approximately 70% of existing RTUs are electromechanically-controlled, with the balance microprocessor-controlled. The above listed faults can be detected in both types of units. Additional alarms such as refrigeration cycle problems including high or charge and low or high pressure, can only be enabled in microprocessor-controlled units and thus were not accepted in the final T24 language.

This Title 24 FDD measure has also been proposed to the NW Energy Codes Group for its consideration. NEEA staff is part of the group and should be in strong support of the proposal. If the NW states adopt this requirement, it will provide impetus for additional states to adopt since it will be clear that there will be equipment coming to market to meet the required standard. The Title 24 FDD measure is also being proposed in the 2015 revision of the IECC and the IgCC .

[21] CEC PIER work led by NBI with WCEC and the Utility Codes and Standards Enhancement (CASE) work led by HMG and PECI.

Detail on Progress Indicator – revised T24 submittal:

SECTION (I) - 120.0 120.6 NR Mandatory Equipment
SUBCHAPTER 3 NONRESIDENTIAL, HIGH-RISE RESIDENTIAL, AND HOTEL/MOTEL OCCUPANCIES, AND COVERED PROCESSES AND INSULATION— MANDATORY REQUIREMENTS FOR SPACE-CONDITIONING AND SERVICE WATER-HEATING SYSTEMS AND EQUIPMENT

(i) Economizer Fault Detection and Diagnostics (FDD). All air-cooled unitary direct-expansion units with an economizer and mechanical cooling capacity at AHRI conditions greater than or equal to 54,000 Btu/hr shall include a Fault Detection and Diagnostics (FDD) system in accordance with NA9 – Fault Detection and Diagnostics. Air- cooled unitary direct expansion units include packaged, split-systems, heat pumps, and variable refrigerant flow (VRF), where the VRF capacity is defined by that of the condensing unit.

Links to final language:
http://www.energy.ca.gov/title24/2013standards/prerulemaking/documents/2011-10-13_14_workshop/review/Draft_Language/Staff_Proposed_Draft_Language-Standards/120.0-120.6_NR_Mandatory_Equipment.pdf

Specific details of the above proposed mandatory measure: - Appendix NA9
http://www.energy.ca.gov/title24/2013standards/prerulemaking/documents/2011-10-13_14_workshop/review/Draft_Language/Staff_Proposed_Draft_Language-Appendices/NA-9-Fault%20Detection%20and%20Diagnostics.pdf

Attachment 1: Original Proposed FDD Standard for RTUs

2011 Title 24 for Nonresidential Buildings requires installation (factory or field), verification, and acceptance testing of a Fault Detection and Diagnostics (FDD) system for Packaged Direct-Expansion Units, as a prescriptive measure. As with any prescriptive measure, this measure can be traded off for another optional measure with equal savings. Credit is given using the Alternative Calculation Method by degrading cooling efficiency by XX% for non-FDD systems and only 5% for FDD systems. This measure supplements the compliance option on Form MECH-12A first included in 2008.

FDD capabilities must be verified in the field by verifying that the FDD hardware is installed and that the equipment make and model includes factory-installed hardware that match the information specified on the manufacturers' cut sheets and design plans. The functionality of the FDD must also be tested in the field. Form ***MECH-XXA*** *is used to verify that the criteria are met.*

Construction Inspection

1. The following **sensors** should be permanently installed to monitor system operation and the controller should have the capability of displaying the value of each parameter:

Refrigerant Pressure	Refrigerant Temperature	Air Relative Humidity	Air Temperature
• Suction Line	• Suction Line	• Outside Air	• Outside Air
• Liquid Line	• Liquid Line	• Supply Air	• Return Air
			• Supply Air

2. The controller will provide **system status** by indicating the following conditions:

• Compressor Enabled	• Free Cooling Available	• Heating Enabled
• Economizer Enabled	• Mixed Air Low Limit Cycle Active	

3. The unit controller shall have the capability to **manually initiate each operating mode** so that the operation of compressors, economizers, fans, and heating system can be independently tested and verified.

4. The unit controller shall have the capability to **detect at least <u>ten</u> of the following faults**:

• Air Temp. Sensor Failure/Fault	• High Refrigerant Charge	• Low Refrigerant Charge
• Compressor short cycling	• Refrigerant Line Restrictions/ TXV Problems	• Refrigerant Line Non-Condensables
• Low Side HX problem	• High Side HX problem	• Capacity Degradation
• Efficiency Degradation	• Not Economizing When it Should	• Damper Not Modulating
• Excess Outdoor Air		

5. Faults shall be reported to a **fault management application** accessible by day-to-day operating or service personnel, or annunciated locally on zone thermostats.

6. A **performance indicator** shall be provided, which will allow tracking of efficiency.

7. The FDD System used shall be **certified by the CEC and verified to be installed correctly**. *Certification and verification procedures are TBD*.

Attachment 2: FDD Roundtable Participants July 2010

Mike Brambley	Pacific Northwest National Lab
Martha Brook	California Energy Commission
Cathy Chappell	Heschong Mahone Group
Mark Cherniack	New Buildings Institute
Bobby DiFulgentiz	Lennox Industries
Martyn Dodd	EnergySoft
Piotr Domanski	National Institute of Standards and Technology
John Douglas	Lennox Industries
Joseph Fleishman	California Energy Commission
Craig Fulgum	Virtjoule
Tom Garcia	CalBO
Sean Gouw	Southern California Edison
Dale Gustavson	Better Buildings Institute, Inc.
Kristin Heinemeier	Western Cooling Efficiency Center
Randall Higa	Southern California Edison
Sherry Hu	Pacific Gas & Electric
Marshall Hunt	Consultant
John Kaufmann	Pacific Northwest National Lab
Golam Kibrya	California Energy Commission
John Kimmes	Target
David Kuo	Johnson Controls
Don Langston	Aire Rite Air Conditioning & Refrigeration, Inc.
Richard Lord	Carrier Corporation
Mike Lubliner	Washington State Energy Extension
Jim McClendon	Walmart
Jon McHugh	McHugh Associates
Jeff Miller	California Energy Commission
John Proctor	Proctor Engineering Group
Mark Rehley	Northwest Energy Efficiency Alliance
Todd Rossi	Field Diagnostic Services, Inc.
Chris Scruton	California Energy Commission
Vern Smith	Architectural Energy Corporation
Danny Tam	California Energy Commission
Stuart Tartaglia	Pacific Gas & Electric
Buck Taylor	Roltay Services, Inc.
Adrienne Thomle	Honeywell
Matt Tyler	Portland Energy Conservation, Inc.
Anne Wagner	Pacific Northwest National Lab
Stuart Waterbury	Architectural Energy Corporation
Mike Walker	Lennox Industries
Larry Wei	Lennox Industries
David Weightman	California Energy Commission
David Yuill	Purdue University-Herrick Laboratory