California Energy Commission's Public Interest Energy Research Program Case Study

Automated Fault Detection & Diagnostics for Rooftop Packaged Air Conditioners

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The Problem

Maintenance for rooftop packaged air conditioners (RTUs) is a rare preventative practice. 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

Automated Fault Detection & Diagnostics (AFDD) for RTUs is a technology class that 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. California's Energy Efficiency Strategic Plan urges the broader application of this technology, and Title 24 requires AFDD as a mandatory measure for all new commercial RTUs.

Faults that Reduce RTU Efficiency

There are many common occurrences that significantly reduce RTU system efficiency. The range of faults includes sensor failures, poorly commissioned control setpoints and calibrations, airflow restrictions, and mechanical component failures. These faults result in a number of different inefficiencies such as failed or inappropriate economizer operation, low thermodynamic efficiency, reduced cooling capacity, and increased fan energy use. Recent research into the prevalence and energy-use penalty of various failures has helped to inform how AFDD tools should prioritize the importance of non-emergency faults, and what types of capabilities should be required of these tools. Table 1 describes the efficiency impact of various common faults, the probability that these faults will occur within a normal equipment lifetime, the likelihood that such a failure would be noticed with and without AFDD tools, and the average energy savings that could be realized from repairing the faults. The failures considered here include:

1. *Air temperature sensor failure.* Damage, disconnected wiring, or mis-calibration of air temperature sensors can cause a rooftop unit to operate in inefficient modes, such as failing to actuate an economizer when outside air can provide free cooling, or remaining in a high-capacity mode in an attempt to maintain supply air temperature when a more energy efficient stage could provide adequate cooling.
2. *Sub-optimal refrigerant charge.* Inappropriate refrigerant charge is one of the most common faults in rooftop air conditioners. It occurs because of improper installation and service practices, or due to leaks in the refrigerant circuit and refrigerant valves. While a system may still be able to provide adequate cooling capacity, low and high refrigerant charge result in decreased efficiency.

FIGURE 1: PREVALENCE OF VARIOUS FAULT TYPES IN RTUS

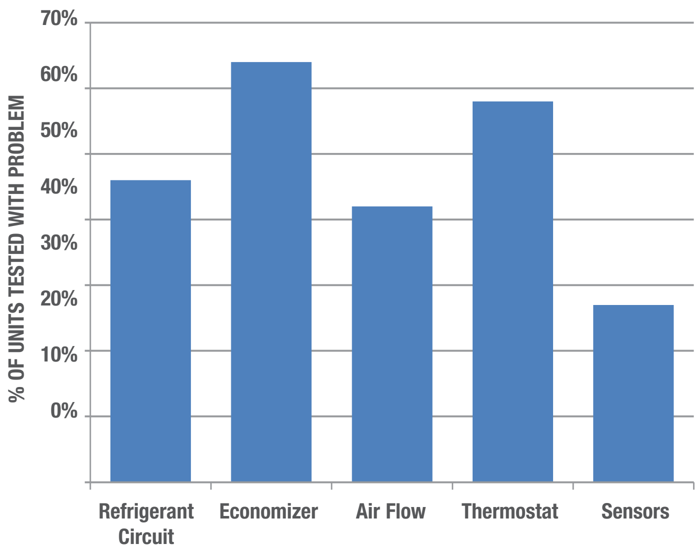

TABLE 1: FAULTS THAT IMPACT ENERGY PERFORMANCE OF RTUS *(Assumptions taken from Heinemeier et al, 2011)*

FAILURE MODE	EFFICIENCY PENALTY	PROBABILITY OF FAULT (15 YEARS)	PROBABILITY OF DETECTION W/ AFDD	PROBABILITY OF DETECTION W/O AFDD	AVG. KWH/TON-YR SAVINGS OVER (15 YEARS)
Low airflow: 300 *cfm/ton*	5%	NA	NA	NA	not modeled for Title 24 code change
Evaporator heat exchange problem, incl. low airflow (50% coil blockage)	5%	74%	75%	25%	
Refrigerant charge: 80% of nominal charge	15%	85%	75%	50%	
Performance degredation: 30% condenser blockage, 300 *cfm/ton*, -10% charge	21%	NA	NA	NA	
Refrigerant line non-condensables	8%	50%	75%	25%	
Condenser heat exchange problem (50% coil blockage)	9%	48%	75%	25%	
Compressor short cycling	10%	30%	75%	25%	
Refrigerant line restrictions/TXV problems	56%	62%	75%	25%	
Air temperature sensor failure	not a comparable efficiency penalty	2%	75%	25%	9.5
Non-optimal economizer set point (55°F instead of 75°F)		30%	75%	75%	448
Economizer damper failure		24%	75%	25%	535
Excess outside air		24%	75%	25%	136

According to research by Robert Mowris of Verified Inc., a system that is charged 20% lower than manufacturer's nominal recommendations can result in a 15% efficiency degradation.

3. *Low airflow.* Low supply airflow occurs when fan speed is not appropriately commissioned, or when there is some airflow restriction, such as a blocked coil, dirty filter, or major point of resistance in the air distribution system. Airflow below 300 cfm/nominal-ton can cause significantly reduced cooling capacity, and increased compressor power. If airflow is low enough it can cause an evaporator coil to ice, could allow liquid refrigerant to pass through the compressor, and might cause short cycling of the compressor.

4. *Condenser or evaporator coil heat exchange problems.* This occurs when there is low airflow through the evaporator or condenser coil, generally caused by coil blockage, or fan failure. Low airflow through the evaporator coil can cause incomplete refrigerant vaporazation and results in liquid flooding the compressor which wastes energy and will damage the compressor.

5. *Refrigerant line contaminants.* When non-condensable contaminants such as air and water vapor are introduced into a refrigerant circuit, the system operates less efficiently because heat transfer surface is reduced, and compression power increases. This is most commonly caused by leaks, or poor service practices such as failing to completely evacuate refrigerant lines when charging equipment.

6. *Refrigerant line restrictions.* Flow constriction due to blockage in the refrigerant line causes flow resistance, which impacts system operating pressures, and starves flow to system components. This causes reduced cooling capacity as refrigerant flow is reduced, and increases compressor power since additional pressure drop must be overcome. When a restriction is present in the liquid line, it can cause a larger than normal vapor expansion pressure drop which may cause freezing on the evaporator coil. These restrictions can be caused by dirty suction filters, fouled expansion devices, dirty liquid line filter/dryers, a joint partly filled with solder, or physical damage resulting in bent or crimped refrigerant lines. According to research by the Texas A&M Energy Systems Laboratory, liquid line restriction can reduce EER by 56%, while other restrictions can impact performance by 25%.

7. *Compressor short cycling.* Compressor short cycling can be caused by coil blockage, equipment oversizing, and poor thermostat location, among other reasons. It is characterized by repeated run times shorter than three minutes. Since it takes several minutes for an RTU to achieve steady state and full cooling capacity,

short cycling can result in a significantly decreased average efficiency, even if there are no physical failures in the equipment. According to AEC's Small HVAC System Design Guide, short cycling can cause efficiency penalty of approximately 10%. In addition to the energy cost, short cycling is one of the most common causes for early equipment failures, since the undue cycling impacts several components adversely.

8. *Sub-optimal economizer setpoint.* Economizer damper actuation is controlled by an outdoor air temperature setpoint which is supposed to return the outdoor air damper to a minimum ventilation position when the outside air is too warm to provide free cooling. An economizer set to changeover at 55˚F significantly limits the number of hours for economizer operation compared to a 75˚F setpoint, as Title 24 recommends for most California climate zones. Some economizers have adjustable setpoints, while others do not, but it is common that setpoints are not selected correctly, resulting in missed opportunities for economizer cooling. The opposite problem can occur as well. When a setpoint is higher than recommended or when an outside air damper is stuck open, heating and cooling energy will increase significantly.

9. *Economizer damper failure.* Often, economizers fail to actuate at all. This can be due to a motor failure, link failure, or jammed damper blade. The failure results in significant energy inefficiency, either because of an undue addition of heating and cooling load when stuck open, or a missed opportunity for free cooling when a damper is stuck closed.

10. *Excess outside air.* When an economizer damper is stuck open, or when a system is commissioned with a higher than necessary ventilation rate, it causes an energy penalty because of additional heating and cooling load. The energy penalty of this fault differs by climate zone, but can dramatically increase energy use for heating and cooling.

Figure 1 summarizes results of research by the New Buildings Institute which describes the prevalence of different fault types in RTUs. Importantly, it was found that 64% of economizers suffer from faults and failures.

Methods for Detecting Faults

There are various technical strategies to detect and diagnose faults. Each method takes a different approach on what points to measure in a system, and how to interpret measurements as distinct indication of particular faults. Some fault detection strategies measure refrigerant circuit variables only, such as temperatures and pressures, to alarm when there is an identifiable problem. Some monitor the air-side of the system to detect deficiencies. Other strategies use electric power measurements, or vibration as a proxy to identify various operating modes, and can identify the presence of faults based on operating history, and signal patterns compared to nominal expectations. Some methods are able to diagnose faults and their underlying causes explicitly, while others are designed to send alarm signals when there is a clear degradation in system performance. Each strategy has different cost effectiveness implications, and technical energy savings potential according to what faults it is able to capture. In 2010 and 2011 the Western Cooling Efficiency Center installed and evaluated several different fault detection technologies in an effort to understand and characterize their range of capabilities. Table 2 compares nine different specific AFDD technologies by their technical ability to measure particular faults.

California Title 24 Requirements for AFDD

Since 2008 AFDD for RTUs has been a Title 24 compliance option, but the requirements for fault detection capabilities were not explicitly defined, and the technology has not been broadly applied. The research results presented in this case study informed the recent Title 24 requirement for AFDD as a mandatory measure for all new commercial unitary DX systems with an economizer and mechanical cooling capacity larger than 4.5 tons. This includes split systems, and variable refrigerant flow systems with economizers. Development of the requirement was supported by a broad industry stakeholder collaboration through the Western HVAC Performance Alliance. The mandatory requirements become effective January 1, 2014. An evaluation of cost effectiveness and potential energy savings for the range of technology capabilities resulted in prioritization of the most important faults to detect. The code language requires AFDD to detect and communicate the following faults:

1. Air temperature sensor failure/fault
2. Not economizing when it should
3. Economizing when it should not
4. Damper not modulating
5. Excess outdoor air

Compliance will require laboratory testing for certification of fault detection technologies, and in-field verification of AFDD functionality for all new RTUs. In parallel to the Title 24 code change, the Western HVAC Performance Alliance AFDD Committee has launched a Project Committee for ASHRAE Standard 207.P to define a protocol for certification of AFDD technologies.

While there are several third-party AFDD tools available, it is anticipated that OEM's will begin to include these fault detection capabilities within standard production models, since many new RTU's already have alarm codes associated with certain faults. The most important shift will be toward communicating faults off-board so that they are actually addressed. Title 24 code requires AFDD technologies to annunciate faults detected to some form of fault management tool, the zone thermostat, or appropriate facility personnel. When applied universally for all new RTUs in California, it is estimated that annual energy use for RTUs would be reduced by 12%, amounting to more than 30 Million kWh savings across California over the next 15 years.

For More Information

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TABLE 2: COMPARISON OF CAPABILITIES FOR SEVERAL AFDD TECHNOLOGIES

	FDSI INSIGHT V.1 PRODUCTION	SENSUS MI	CLIMACHECK	SMDS	NILM	LOW COST NILM	SENTINEL/INSIGHT BETA TESTING	VIRTJOULE	LOW COST SMDS
Low Airflow	●	●	●		●	●	●	●	
Low/High Charge		●	●		●	●	●	●	
Sensor Malfunction	●	○	●	●			●	○	
Economizer non Functioning	●	○	○	●			●	●	
Compressor Short Cycling	●	○	●		●	●	●	●	●
Excessive Operating Hours	●	○	●				●	●	●
Performance Degradation		●	●	●	●	●	●	●	●
Insufficient Capacity	●	○	●				●	○	●
Incorrect Control Sequence	●	○	●		●	●	●	●	
Lack of Ventilation	●	○		●			●	○	
Unnecessary Outdoor Air	●	○	○	●			●	○	
Control Problems	●	○	●	●			●	●	
Failed Compressor	●	●	●	●	●	●	●	●	
Stuck Damper	●	●	●	●			●	○	
Slipping Belt	●	●	●		●		●	●	
Leaking Valves			●		●		●	○	
Unit Not Operational	●	○		●	●	●	●	●	●

●=STANDARD CAPABILITY ○=EXTENDED CAPABILITY

About PIER

This project was conducted by the California Energy Commission's Public Interest Energy Research (PIER) Program. PIER supports public interest energy research and development that helps improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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