# Smart Maintenance For Rooftop Units

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Associate Member Member ASHRAE Member ASHRAE

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Packaged HVAC equipment is the most common source for HVAC in small and medium commercial buildings, including retail stores, supermarkets, and restaurants. The U.S. Department of Energy estimates that rooftop and unitary air-conditioning equipment accounts for about 1.03 out of a total of 1.66 quads (62%) of total energy consumption for cooling the current building stock of commercial buildings in the United States. Generally, packaged equipment is smaller, more numerous, and not as well maintained as large built-up systems. Because of the large numbers, service technicians cannot afford to spend much time on each unit. In addition, the units are not located in highly visible equipment rooms where it is convenient for onsite technicians to visit daily.

Rooftop units are often “out-of-sight, out-of-mind” and completely ignored until performance has degraded to a point where the unit is no longer providing adequate cooling. Based on these facts and their own experiences, the authors believe that the actual field performance of rooftop units is degraded from design intent more severely than their central plant counterparts. However, additional work is needed to document performance degradations associated with rooftop units operating in the field.

Some changes are occurring to improve the situation. For instance, a growing trend is outsourcing facility management services to companies that specialize in facility maintenance and energy services. In addition, new technologies are being developed to aid maintenance and service practices. Some service providers are applying these new technologies to provide “smart maintenance” for rooftop air-conditioning equipment, for improving comfort and reliability while reducing costs through longer equipment life and lower energy consumption. Since these companies manage large aggregated portfolios of properties and assume energy and maintenance budget responsibility for these properties, they have the scale and the incentives to apply this technology to increase profits and separate their service delivery offerings from their competitors.

## What Is Smart Maintenance?

Smart maintenance involves the application of technology to identify when maintenance is required and to monitor performance and diagnose problems more quickly and accurately than through traditional means. A tradeoff exists between the costs associated with providing maintenance and the associated benefits (improved energy efficiency and longer equipment life). If maintenance inspections are performed too frequently, labor costs exceed the benefits. On the other hand, if maintenance is provided too infrequently or not at all, the system degrades, which leads to lower efficiency and the possibility of premature equipment failure. Deciding when service should be performed is only half of the equation. The other half of smart maintenance is anticipating service needs without relying exclusively on human expertise. This can be accomplished by using automated fault diagnostic systems.

This article addresses two issues for rooftop air conditioners: identification of faults that drive maintenance costs and performance degradations, and common approaches to smart maintenance that reduce operating costs.

## Degradation and Failure

To better understand the types of faults that occur in unitary air-conditioning equipment, a database from a HVAC service company that primarily services rooftop air conditioners for retail stores was

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## About the Authors

**Mark Breuker** is director of national energy accounts at Service Resources, Atlanta. He is a member of ASHRAE Technical Committee 4.11, Smart Building Systems.

**Todd Rossi,** Ph.D., is vice president of science and technology at Field Diagnostic Services, Pa.

**James E. Braun,** Ph.D., is an associate professor of Mechanical Engineering at Purdue University. He is chairman of TC 4.11.

| Causes for 'No Air-Conditioning' Service Call | % Total Occurrences |
|---|---|
| Controls Error | 21% |
| Electrical Problem | 20% |
| Refrigerant Leak | 12% |
| Condenser | 7% |
| Air Handling | 7% |
| Evaporator | 6% |
| Compressor | 5% |
| Cooling Water Loop | 4% |
| Plugged Filters | 2% |
| Personnel Error | 2% |
| Expansion Device | 2% |
| Can t Classify | 12% |

Table 1: Classification of 'no air-conditioning' cases.

| General Classification Of Faults | % of Total Service Costs |
|---|---|
| Compressor | 24% |
| Controls Error | 10% |
| Condenser | 9% |
| Electrical Problem | 7% |
| Evaporator | 6% |
| New Installation | 6% |
| Air Handling | 5% |
| Refrigerant Leak | 5% |
| Installation/Startup | 4% |
| Cooling Water Loop | 4% |
| Fan Belt | 2% |
| Others | 18% |

Table 2: Classification of fault types by total cost.

analyzed. The result of this work was originally published in ASHRAE's *International Journal of Heating, Ventilating, and Air Conditioning and Refrigerating Research* (Breuker and Braun 1998a). The database that was used for this work contains more than 6,000 separate fault cases from 1989 to 1995. Frequency of occurrence and total cost of repair for different faults were estimated using a statistically representative subset of the data. Frequency of occurrence information helps to expose the "nuisance" faults—those faults that are not expensive to fix, but cause a periodic loss of comfort and frequent visits from service technicians. Total cost of repair data targets those faults that dominate service costs.

*Table 1* shows the frequency of occurrence of faults that led to inadequate building comfort conditions, termed "no air conditioning" by service personnel. For this classification of faults, approximately 40% of the failures were electrical- or controls-related and the other 60% were mechanical. However, motor failures were classified with the equipment that they power (e.g., condenser motor fans with condenser). If motor failures are reclassified under the "electrical problem" category, electrical and control failures accounted for about 60% of the failures, while mechanical problems accounted for 40%.

*Table 2* shows the service costs associated with repairs as a percentage of the total costs of service provided for different faults. Although compressor failures do not occur as frequently as other faults, they are the most costly failure for unitary air conditioners. The labor and component costs are high for replacing compressors. The costs associated with controls and electrical faults are also high due to their high repair frequency. The combined refrigeration cycle faults (condenser, evaporator, air handling, and refrigerant leakage) accounted for approximately 25% of costs.

*Table 3* gives a cost breakdown of the diagnoses associated with compressor faults. Approximately 70% of the classified faults were associated with motor problems. Another important fault, termed "internal bypass/inefficient," refers to a loss in compressor capacity due to compressor valve leakage or other leakage paths. This fault causes degradation in performance that is not detected typically until comfort is compromised. In addition, both "internal bypass" and "broken compressor internals" can lead to motor failures (open windings, short to ground) if the compressor is allowed to operate in this condition for a long time.

Conditions that lead to compressor failures were investigated through interactions with industry personnel (McGrue 1995 and Janaushek 1995). Although most failures in hermetic compressors are diagnosed as a failure in the motor, these failures are usually the result of a mechanical problem that overloads the motor. Furthermore, the presence of liquid refrigerant in the compressor is known to be a primary cause of mechanical failures in positive displacement compressors.

The presence of liquid in the compression chamber damages valves, rods, and pistons. Also, if liquid refrigerant is held in the compressor during startup (i.e., flooded start), oil is carried out of the compressor shell, resulting in a temporary loss of lubrication until it circulates around the refrigeration circuit and returns to the compressor. Cool mornings cause liquid refrigerant to pool in the compressor, resulting in a flooded start. Continuous liquid floodback caused by a lack of suction superheat, cools the compressor body. When the system shuts down, the liquid refrigerant collects in the cool compressor shell, resulting in a flooded start when the system restarts. Since many air conditioners operate with "on-off" control, a system could go through many flooded starts per day if liquid floodback is present. Some causes of liquid floodback are fouled evaporator coils, fouled condenser coils, refrigerant overcharge, and a faulty TxVs.

Other conditions that lead to early compressor failure include high compressor temperatures and electrical supply problems, such as low voltage and voltage spikes. High compressor temperatures are caused by condenser fan failures, condenser fouling, liquid line restrictions, and low refrigerant charge.

## Degradation Faults and Performance

In addition to investigating the cause of failures in unitary air-conditioning equipment, Breuker and Braun (1998a) also investigated the effect of five common degradation faults on performance. These five faults include refrigerant leakage, condenser fouling, evaporator fouling, compressor valve leak-back, and liquid-line restrictions.

*Table 4* shows the average impact of the five faults on cooling capacity, coefficient of performance (COP), and compressor suction and discharge temperatures. These performance indices provide a means of comparing the impact of different faults and quantifying the level at which faults become important. Reductions in capacity and efficiency are important because they result in higher energy bills and loss of comfort for the building occupants, whereas no superheat or high discharge temperatures lead to early compressor failure. Refrigerant leakage, liquid-line restriction, and evaporator fouling have a greater effect on capacity than COP. Condenser fouling affects COP more than capacity, and compressor valve leakage affects both about the same. Refrigerant leakage, liquid line restriction, and condenser fouling lead to higher compressor temperatures. Evaporator fouling, compressor valve leakage, and condenser fouling cause low suction superheat.

## Typical Maintenance Programs

As the preceding discussion shows, the effect of degradation faults on rooftop unit performance and equipment life is significant and provides strong incentives to keep up with rooftop unit maintenance. However, many rooftop units in noncritical applications are only serviced upon failure of a major component or when the extreme loss of performance leads to the system no longer providing sufficient cooling capacity to maintain building comfort. Although this approach achieves savings in the short term (since no money is spent on maintenance), it is expected that higher energy consumption and shortened equipment life will result in higher overall operating expenses as compared with application of smart maintenance. However, more work is needed to document the energy penalties and reduced life associated with minimal maintenance practices.

Common ways to intelligently perform rooftop unit maintenance that are discussed include: scheduled preventative maintenance; responding to information obtained from remote monitoring; and condition-based maintenance based on automated fault detection and diagnostic (FDD) systems.

## Scheduled Preventative Maintenance

Scheduled preventative maintenance is a common way to ensure consistent and efficient performance from a rooftop air conditioning unit. Types of work that usually are part of a preventative maintenance on a rooftop unit include:

- Changing the filter.
- Using refrigeration cycle measurements to check refrigerant charge levels and the need to clean heat exchangers.
- Inspecting/replacing belt.
- Checking fan bearings and lubricate if appropriate.
- Inspecting condensate drain.
- Inspecting electrical system, including a visual inspection for contactor wear.
- Checking economizer motion.

| Description of Compressor Fault | % of Total Category Cost |
|---|---|
| Short to ground | 25% |
| Open windings | 17% |
| Locked rotor | 16% |
| Broken compressor internals | 11% |
| Internal bypass/inefficient | 8% |
| Other replacements | 19% |
| Other non-replacement problems | 4% |

Table 3: Compressor fault cost breakdown.

Filter-changing and inspection schedules can vary greatly depending on the application of the equipment. Filters can be changed as frequently as once per month or once per year depending on airborne dirt levels at the facility. Mechanical equipment inspection schedules generally occur once or twice during both the heating and cooling seasons. Monthly inspections of all equipment may be used in critical applications.

If the environment is predictable and the inspection schedules are tailored specifically to the application, then preventative maintenance can accomplish the first goal of smart maintenance (providing service visits only when required). However, because of the unpredictability of many applications, more advanced techniques are often required to achieve this goal.

## EMS Monitoring

More and more often, managers of small- to mid-size buildings that typically use rooftop units are specifying low-cost energy management systems (EMS). The increase in the number of EMS systems in small buildings and the accessibility to communication technologies are enabling remote monitoring of large portfolios of properties from a central monitoring center. Rooftop units that are tied into an EMS can have a high-level inspection performed without having a trained technician setting foot on the roof. With remote monitoring, a technician contacts the EMS system in a building on a regular basis to verify scheduling of equipment, change schedules and control strategies, and download alarms and trend data. Downloaded data gives the monitoring technician the ability to make an assessment of the building's overall performance and the performance of major subsystems in the HVAC system.

What kind of rooftop unit maintenance needs can be detected via remote monitoring of typical EMS systems? This depends on the type of sensors that are available on the roof-

**Changes in rooftop operation due to refrigerant leakage**

| (% leakage) | % Change in Capacity | % Change in COP | Change in $T_{sh}$ ( F) | Change in $T_{hg}$ ( F) |
|---|---|---|---|---|
| 3.5 | 3.0 | 2.7 | 3.5 | 3.3 |
| 7.0 | 3.8 | 2.8 | 7.0 | 6.1 |
| 10.5 | 5.6 | 3.6 | 9.9 | 8.4 |
| 14.0 | 8.0 | 4.6 | 11.1 | 10.0 |

**Changes in rooftop operation due to liquid line restriction**

| (% $\Delta$P) | % Change in Capacity | % Change in COP | Change in $T_{sh}$ ( F) | Change in $T_{hg}$ ( F) |
|---|---|---|---|---|
| 5 | 3.5 | 3.0 | 5.5 | 5.8 |
| 10.0 | 5.2 | 3.7 | 8.7 | 8.8 |
| 15.0 | 8.8 | 5.1 | 11.9 | 12.2 |
| 20.0 | 17.2 | 8.7 | 16.0 | 16.6 |

**Changes in rooftop operation due to compressor valve leakage**

| Fault Level (% $\Delta \eta_v$) | % Change in Capacity | % Change in COP | Change in $T_{sh}$ ( F) | Change in $T_{hg}$ ( F) |
|---|---|---|---|---|
| 7 | 7.3 | 7.9 | -3.6 | 0.2 |
| 14 | 9.6 | 10.5 | -4.8 | 0.0 |
| 28 | 12.5 | 14.0 | -7.2 | 0.1 |
| 35 | 21.3 | 23.8 | -11.8 | 0.6 |

**Changes in rooftop operation due to condenser fouling**

| (% area block) | % Change in Capacity | % Change in COP | Change in $T_{sh}$ ( F) | Change in $T_{hg}$ ( F) |
|---|---|---|---|---|
| 14 | 3.1 | 4.3 | 0.8 | 2.2 |
| 28 | 4.8 | 7.7 | 4.2 | 2.6 |
| 42 | 7.4 | 12.2 | 8.0 | 3.1 |
| 56 | 10.9 | 17.9 | 11.2 | 4.5 |

**Changes in rooftop operation due to evaporator fouling**

| (% $\Delta$ airflow) | % Change in Capacity | % Change in COP | Change in $T_{sh}$ ( F) | Change in $T_{hg}$ ( F) |
|---|---|---|---|---|
| 12 | 6.7 | 6.0 | 2.1 | 1.5 |
| 24 | 13.6 | 12.3 | 3.9 | 3.2 |
| 36 | 19.4 | 17.4 | 5.5 | 5.1 |

Table 4: Effect of degradation faults on a 3-ton (10.6 kW) rooftop unit with a fixed-orifice expansion device.

top units tied into the EMS system. In the extreme case, the technician could examine temperatures and pressures required to perform basic diagnostics. For example, a differential pressure signal can be used to spot a filter in need of replacement. An evaporator pressure and suction temperature could be used to flag an excessively low or high refrigerant superheat at the inlet to the compressor. In reality, however, this level of instrumentation is usually not available on rooftop units.

In more cases, detection of a loss of performance is the best that can be achieved via remote EMS monitoring. For example, the monitoring of rooftop unit cycling frequency as a function of the indoor and outdoor temperature, or the rate at which the system can achieve the cooling setpoint after a night setback, both provide an early indication of capacity loss resulting from degradation faults. Once a potential problem is spotted via remote monitoring, a trained technician can be dispatched to the building for a more detailed diagnosis of the problem and resulting repair.

## Early Detection & Diagnosis Of Degradation Faults

Rossi and Braun (1997) developed a technique that uses only temperature measurements to detect and diagnose five commonly occurring faults in rooftop air-conditioning systems. This method relies on a steady-state model to predict seven temperatures used by the method as a function of three driving conditions, outdoor air temperature, return air temperature, and return air humidity. Detection and diagnosis are accomplished statistically, so the uncertainly of the measurements and model predictions must be estimated properly for the technique to work.

Breuker and Braun (1998b) tested the sensitivity of the FDD method in a laboratory setting. The rooftop air-conditioning unit was operated in a simulated building using typical "on-off" control over a range of operating conditions and fault levels.

What conclusions were reached from this work?

Good performance was achieved in detecting and diagnosing five faults using a "low-cost design with only six temperatures (two input and four output) and linear models." Refrigerant leakage, condenser fouling, and liquid line restriction were detected and diagnosed before an 8% reduction in capacity or COP occurred. The technique was less sensitive to evaporator fouling and compressor valve leakage, but was still able to detect and diagnose compressor valve leakage before a 12% reduction and evaporator fouling near a 20% reduction in capacity and COP. On average, the performance improved by about a factor of two when ten measurements (three input and seven output) and higher order models were used.

## FDD Technology

The ideal maintenance program would maintain comfort and safe equipment operation at minimum combined service and energy costs (Rossi and Braun, 1996). The effective use of equipment performance information to manage the service process is the key to approaching this ideal.

Obtaining equipment performance information is an important first step. Placing cost aside, permanently installing sensors (e.g., refrigerant pressure, refrigerant temperature, secondary fluid temperatures and power consumption) on every rooftop unit and processing the data intelligently via on-board computers to determine service needs is ideal. However, the cost of instrumenting each system can be relatively high compared to the savings potential. An alternative approach is to provide service technicians with intelligent tools allowing expensive components to be used repetitively on different units. A variety of hybrid approaches also makes sense. The best approach depends on how critical the application is and how labor and instrumentation costs compare.

Once performance information is available, it is important to integrate it into the service management process to achieve the cost reduction and reliability improvement goals. This can be done by using the information to anticipate when performance degradations (e.g., dirty filters and coils) justify servicing, verifying that service was performed successfully, calling for immediate emergency service when unanticipated failures occur, and prioritizing service by overall cost. The authors have been involved with several studies that have helped lay the groundwork for achieving this vision, including:

- Identification of important faults (Breuker and Braun 1998a).
- Development of rooftop unit modeling tools for predicting the effects of faults on performance (Rossi 1995, Rossi and Braun 1999, Leroy et al. 2000).
- Development of cost effective fault detection and diagnostic methods (Rossi and Braun 1997).
- Development of optimal service scheduling algorithms (Rossi and Braun 1996).
- Laboratory performance evaluations (Breuker and Braun 1998b).

Commercial products are available that provide performance assessments and automated diagnostics for rooftop units. However, much work is still needed to achieve "smart maintenance." In particular, a need exists to evaluate the overall benefits associated with applying FDD technologies on a widespread basis. This is a difficult problem, because the benefits include many different aspects that may be difficult or require a lot of data to quantify, including reduced utility costs, reduced service costs, increased equipment life, and increased occupant productivity due to reduced downtime and better comfort conditions. Decision makers need this information to justify the investments necessary to put this technology into practice.

One important step toward the widespread application of FDD would be for service organizations and facility managers to integrate equipment performance information into their management processes. This step should help encourage the further development of integrated performance measurement and service management tools. When this is accomplished, it is hoped that the resulting products will address many issues service organizations face today. For instance:

- The shortage of skilled labor could be addressed, since FDD tools should enhance and support all technician skill levels.
- A new level of customer service could be achieved through documentation of the need for service and the anticipated benefits, providing more consistent service, and verifying that service was done properly and what actual benefits were achieved.
- Outcomes management programs based partially on equipment performance information could be used as a basis for evaluating and compensating field personnel.

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## ASHRAE TC 4.11, Smart Building Systems

ASHRAE Technical Committee (TC) 4.11, Smart Building Systems, is concerned with the development and evaluation of technologies that could enable the widespread application of smart building systems.

"Smart" buildings should take advantage of automation, communications, and data analysis technologies to operate in the most cost-effective manner.

This implies integration of building services such as HVAC, fire, security, and transportation; the automation of many operation and maintenance functions traditionally performed by humans; and the interaction with outside service providers such as utilities, energy providers, and aggregators. Currently, three subcommittees form the backbone of the TC's activities: technology development, communications and integration, and testing and evaluation.

Much of the current work in the committee revolves around automated fault detection and diagnostics.

To become involved in the committee, contact Jim Braun, the TC 4.11 chair, at jbraun@ecn.purdue.edu.