Upstream Solutions to Downstream Problems: Working with the HVAC and Efficiency Communities to Improve Field Performance of Small Commercial Rooftop Units

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ABSTRACT

Small commercial HVAC systems are notorious for consuming more energy than necessary to properly heat, cool, and dehumidify buildings. Several studies have confirmed poor performance of the equipment. Key findings include failed economizers, cycling fans, refrigeration charge variations, higher unit external static pressure, and reduced air flow rate. These problems result in a reduction in unit efficiency under field conditions relative to rated conditions and, in some cases, inadequate ventilation to meet occupant needs or building standards. The energy wasted as a result of these problems in newly installed packaged units in California alone is on the order of 830 GWh of electricity, 245 MW of coincident peak demand, and 2.31 million therms of natural gas each year, and compounds each year as new buildings are added to the stock.

This paper focuses on a market transformation effort aimed at HVAC equipment manufacturers to encourage improvements in the overall reliability and maintainability of their product. Enhanced component reliability, fault tolerant design, and/or on-board diagnostic systems are possible solutions being considered under this initiative. The goal of these efforts is to encourage the development of advanced rooftop units with improved reliability that can be identified and promoted by a network of market transformation and energy efficiency programs.

The paper discusses the early involvement of the efficiency and manufacturing communities and the evolution of these efforts. The outcomes of these industry-to-industry communications are highlighted to provide valuable information for future efforts to improve in-field performance.

Introduction

Since the early 1990s, several research projects have been conducted to investigate the field performance of small packaged rooftop air conditioning systems in light commercial applications. Each of these projects reached a similar conclusion: the field performance of small HVAC systems is poor, resulting in excessive energy consumption and reduced ability to deliver energy savings for new, high-efficiency equipment.

Why Small HVAC?

Direct-expansion (DX) air conditioners and heat pumps cool more than half the total commercial new construction floor space in California, as shown in Figure 1 (CEC 2003). Of these systems, single package rooftop air conditioners dominate the market, representing approximately three-quarters of the total DX system capacity. The California rooftop air conditioner market is dominated by small systems, defined here as systems ten tons and smaller, representing almost 60% of the total installed DX cooling capacity. The most popular unit size (in terms of units sold) is five tons (Figure 2).

Figure 1. Floor Space Distribution of HVAC Systems in New Commercial Buildings in California

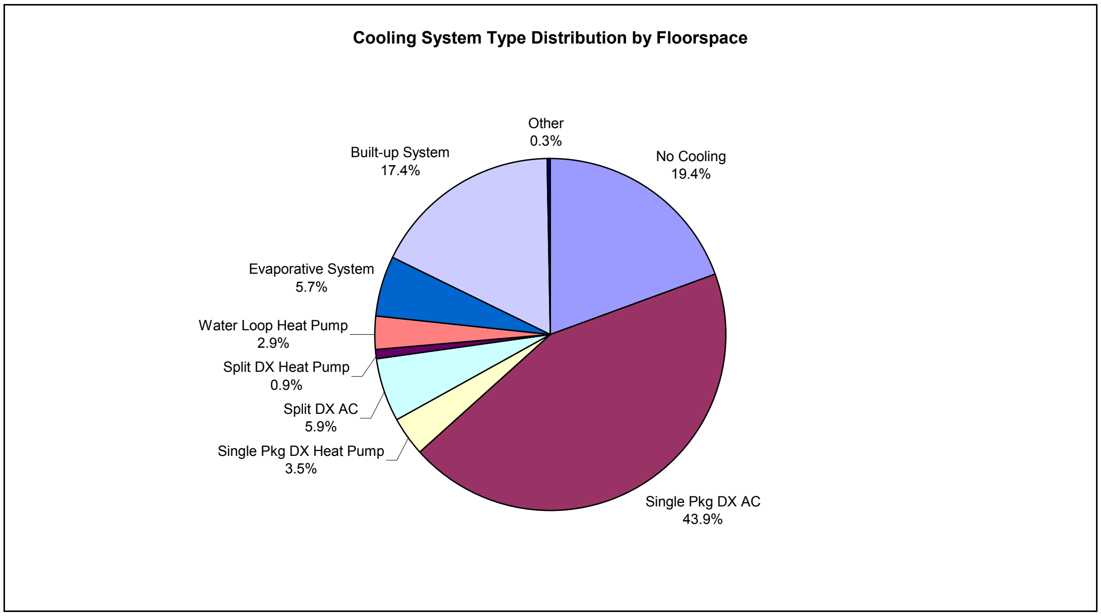
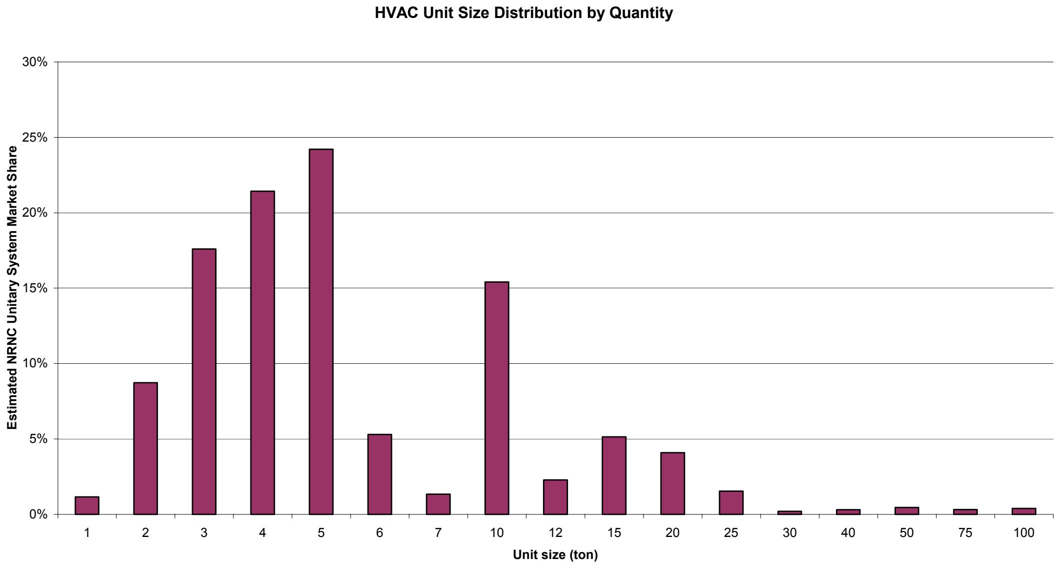


Figure 2. Distribution of Packaged DX System Size by Number of Systems in California



The national market for packaged rooftop units is similar to the California market with these units cooling approximately 45% of the total floor space of 58.7 billion square feet in the United States (EIA 1998). These small rooftop units (RTU) are the "workhorses" of the commercial building industry, yet many systems fail to reach their full potential due to problems with design, installation, and operation.

Field Problems

In the fall of 2003, the New Buildings Institute (Institute) concluded a three-year Public Interest Energy Research (PIER) project for the California Energy Commission (CEC) (CEC 2003). The research was overseen by a technical advisory group consisting of industry, government laboratory, and efficiency community representatives, who participated in the development of the research plan and reviewed the research results. The goal of the project was to investigate the as-installed condition of new small commercial rooftops and investigate opportunities for improving the efficiency of these systems. Teams of engineers, led by Architectural Energy Corporation, were sent into the field to study the as-installed and as-operated conditions of the systems. Buildings four years old or newer were randomly selected for the study to represent the range of commercial new construction activity in the state. The project identified a number of problems with HVAC systems as they are installed and operated in the field. The findings, along with findings from similar projects, are summarized as follows:

Economizers

Economizers showed a high rate of failure in this study, with a total failure rate of 64%. These results are consistent with other studies on economizer reliability in packaged rooftop units:

- A study conducted by the Pacific Gas and Electric Company found an 80% economizer failure rate in existing packaged rooftop units (Felts and Bailey 2000).
- A study conducted for the New England Electric System showed a failure rate of 66% in units two years old or newer (NEES 1993).
- A Northwest Energy Efficiency Alliance (NEEA) project conducted by Portland Energy Conservation Inc. (PECI) identified failure rates of 65% for economizers for small commercial rooftop units (Goody et al. 2003).
- A study prepared for the Eugene Water & Electric Board found economizer air flow and functioning problems on close to 70% of a small number of units checked. (Davis, et al. 2002)

Problems with economizer systems result from catastrophic mechanical and electrical failures, incorrect accessory economizer installation, leaky return dampers preventing 100% outdoor air flow, excessive relief system pressure drop, inaccurate or drifting sensors, incompatible economizer and thermostat controls, and/or incorrect economizer controller field setup. Properly functioning and operated economizers can provide anywhere from 10-60% cooling energy savings depending on the climate and building type. These potential savings demonstrate why improving the operation of economizers is a high priority.

Refrigerant Charge

Service gauges and temperature sensors were used to verify the state of refrigerant charge of the rooftop unit, using the CheckMe![1] Procedure. Any system not meeting the target

[1] CheckMe! is a product of the Proctor Engineering Group, San Rafael, CA.

temperature within five degrees failed the screening test. Of the units where refrigerant charge was tested, 46% did not pass the screening test. The energy impacts of the charge variation (not including units that were fully discharged and obviously leaking) were about five percent of the annual cooling energy. This trend seems to worsen as machines age. A recent study (Proctor 2000) of refrigerant charge in older units found that 62% of the units were not properly charged, with an annual cooling energy impact of 11%. The PECI/NEEA study (Goody et al. 2003) found that 72% of units tested had problems with the refrigerant circuit.

Air Flow

Units were tested for in-situ air flow using a series of flow grids. About 70% of the units tested had air flow of 350 cubic feet per minute per ton (cfm/ton) or less. 39% had air flow less than 300 cfm /ton. The average air flow rate was 325 cfm/ton. The Air Conditioning and Refrigeration Institute (ARI) -rated capacity and efficiency is generally based on air flow rates of 400 cfm/ton. The annual energy impact of low air flow is about 9% of the annual cooling energy. These results are similar to the PECI/NEEA study (Goody et al. 2003), where 62% of the units tested had inadequate air flow.

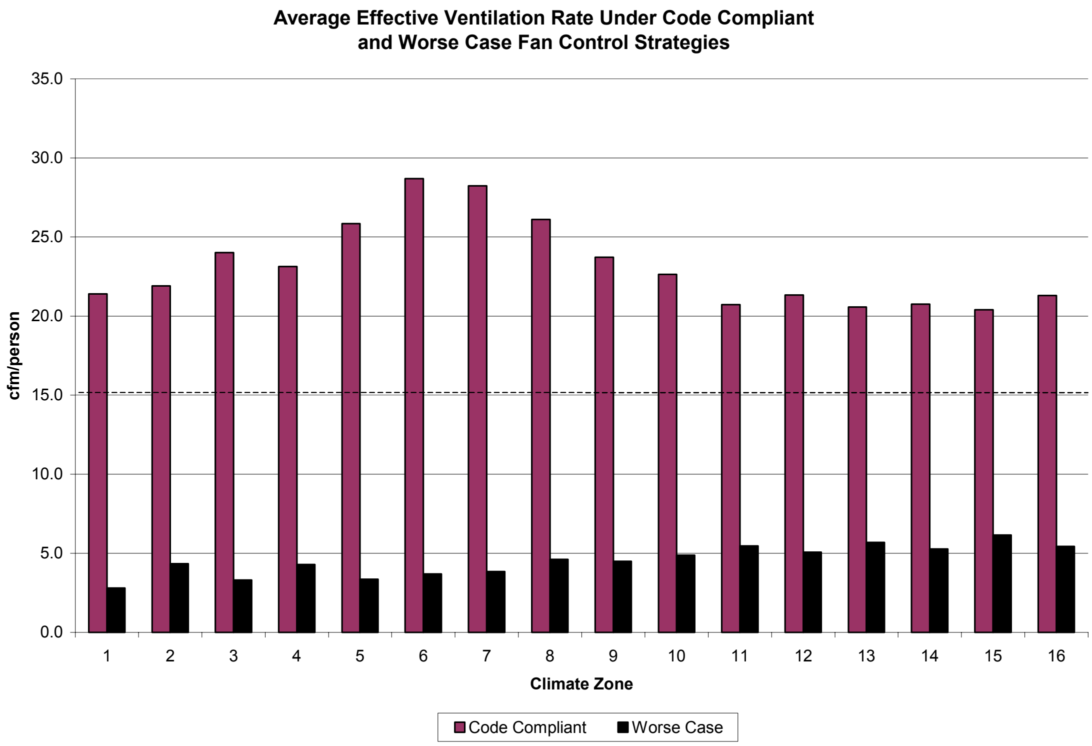
Discrepancy Between Field and Rating Conditions for Supply Fan Power

Testing conducted under the PIER/Institute project indicated that field conditions are more severe than rating conditions with respect to unit external static pressure drop and supply air flow rate. Average external static pressure drop was 0.48 in. water column (W.C.), compared with 0.1 in. to 0.25 in. W.C. assumed in the ARI Standard 210/240 rating procedure. The average measured fan power was 0.18 kW/ton, which is about 20% higher than the nominal fan power assumed in Title 24 energy standards (365 W/cfm or about 0.15 kW/ton). Correcting the air flow to 400 cfm/ton will increase the fan power to 0.34 kW/ton. This increase effectively drops the efficiency of a 10.3 EER unit to about 9.1 EER. The combination of high fan power and low flow rate is due largely to excessive pressure drop in the duct systems.

Systems and Controls Incompatibility

Supply fans were observed to cycle fans with a call for heating or cooling in 38% of the units tested. ASHRAE Standard 62-99 requires continuous ventilation air during occupied hours in normally occupied spaces, except those served by natural ventilation. Though cycling the unit supply fan reduces energy consumption, the impact on ventilation rates and indoor air quality can be important. The effect of cycling fan operation on the effective ventilation rate of a space was simulated using a procedure developed by Sherman and Wilson (PG&E 2000). The results of the simulation of effective ventilation rate of a typical small office building in each of the 16 California climate zones under two fan control scenarios are shown in Figure 3. The code compliant fan control strategy represents a continuously operating fan with a functioning economizer set to a minimum outdoor air quantity of 15 cfm/person. The worse case fan control strategy represents an intermittently-operated fan with fixed outdoor air (no economizer) set to 15 cfm/person.

Figure 3. Effective Ventilation Rate for HVAC Units with Continuous and Cycling Fans



Note the effective ventilation rate under the code compliant case exceeds the nominal 15 cfm/person, due to increased effective ventilation during economizer operation. The effective ventilation rate for a system with intermittent fan control and no economizer is on the order of 5 cfm/person, which is one third of the outdoor air intake setting of 15 cfm/person.

Single-stage cooling thermostats commonly used in commercial applications may not provide the capability for implementing integrated economizer and compressor operation, reducing the economizer energy savings. In the PECI/NEEA study (Goody, et al. 2003), 37% of the units tested had thermostat setup problems.

From Field to Factory

Many players in the HVAC supply, installation, and operations and maintenance industries affect the reliability and efficiency of rooftop units. Transforming the market takes strategies, training, and technology improvements that work at different levels of the system life-cycle. Although more are needed, efforts already exist that are trying to address the installation and operations side of RTUs such as the Building Operators Certification, RTU Diagnostic Protocols (PECI 2002), Air Care Plus (Alliance 2004), NYSERDA Energy$mart Unitary HVAC Building Tune-up Training Program and the Title 24 Acceptance Testing Requirement for Nonresidential Buildings (NBI 2002).

To date, market transformation efforts on the equipment manufacturing side have solely addressed compressor efficiency through tiered performance levels promoted by the Consortium for Energy Efficiency based on Energy Efficiency Ratios (EER) and Seasonal Energy Efficiency Ratios (SEER). The market intervention strategy discussed in this paper goes beyond EER and

SEER by working upstream at the factory to influence the development of a more reliable and efficient new product through three fundamental mechanisms:

1. Present compelling and credible research on field performance that raises awareness of the problems with current systems and interest in creating solutions.
2. Engage the energy efficiency and manufacturing parties in review of, and modifications to, possible solutions.
3. Demonstrate product demand by leveraging efficiency program recommendations or requirements for the new "advanced" equipment.

The field findings presented earlier, and the consistency of our findings with the other referenced research, provides the platform for item #1 above. The findings have been published in industry journals and presented at national conferences[2]. Working from these field results allowed us to begin work on the next two mechanisms: dialog with manufacturers to participate in new design options (item #2) and with efficiency managers to raise demand for advanced units (item #3).

Solutions

The first approach to the issue was to develop a specification to promote features thought to address the reliability and serviceability problems encountered in the field. This specification was developed with the input of the Consortium for Energy Efficiency (CEE) High Efficiency Commercial Air Conditioning (HECAC) Committee, a group of commercial air-conditioner efficiency program managers, advocates, and national laboratories. Several steps, or tiers, of the spec were devised.

The proposed Tier 1 is intended to represent a set of readily available equipment options that can be manufactured today, and are fundamental to improving field efficiency, performance, and serviceability. It is intended as the foundation for an advanced rooftop unit and can provide a short-run basis for utilities to upgrade specification requirements within their individual programs. The specification covers economizers, cabinet leakage, minimum SEER and EER, refrigerant control, fan efficiency, and thermostats. The proposed Tier 2 incorporates the specs in the proposed Tier 1 plus additional design features that create a new-to-the-market Advanced Roof Top Unit (ARTU) that delivers greater field efficiency and performance. The components specified in the proposed Tier 2 address installation and checkout functionality, fans, fan controls, advanced diagnostics, and thermostat capability. A performance-based specification was viewed as a future development, since there is a lack of performance-based measures and test protocols to address those aspects of performance. Key aspects of the specification provisions are as follows:

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[2] A series of articles on the results from the NBI/PIER study ran in Heating, Piping and Air Conditioning magazine from Aug – Nov, 2002. Results were presented at the E Source Forum (Nov, 2002), the 2003 National Conference on Building Commissioning, the 2003 ASHRAE Winter Meeting, and the 2003 ACEEE/CEE Market Transformation Conference.

Table 1. Summary Advanced Rooftop Unit Tier 1 Preliminary Specification

Provision	Description
Factory-installed and run-tested economizers	Factory installed and run-tested economizers can reduce field wiring and economizer assembly problems. Economizer failures become a factory rather than installation warranty issue. NBI study results indicated that factory installed (OEM) economizers were more reliable than field-installed economizers.
Improved economizer design	Encourage features such as direct-drive modulating actuators, gear-driven interconnections between outdoor air damper blades and return air damper blades, permanently lubricated bushings or bearings, and enthalpy sensors with solid-state humidity sensing elements. These features can improve the mechanical and electrical reliability of the system.
Low-leakage dampers	Use low-leakage dampers that provide full shut off of return air when economizer is fully open. Return air leakage increases the temperature of the air leaving the economizer, thereby decreasing the economizer cooling effect.
Building pressure relief	Provide relief air dampers or powered exhaust. Locate relief dampers on the unit in a way to prevent re-entrainment of exhaust air into outdoor air intakes. Without a building pressure relief system, building pressure can become excessive, causing problems with door operation and air leakage noise around door seals.
Differential economizer control strategy	Use temperature or enthalpy sensors as appropriate based on the climate. Develop sensor accuracy specifications appropriate to insure proper control. Design economizers for differential temperature or differential enthalpy control, with compressor operation locked out at outdoor temperatures below 45 °F - 55 °F. These control strategies can mitigate some of the control setup problems observed, and maximize the effectiveness of the economizer.
Demand controlled ventilation	Provide the capability to operate under CO_2 (demand controlled ventilation) control. Demand controlled ventilation is a standard feature on many common economizer controllers, which can reduce ventilation air conditioning costs in intermittently-occupied spaces.
Control cabinet leakage	Design cabinets for leakage rates not to exceed 2% of design flow rate at 25 Pa pressure difference. Cabinet leakage becomes important as duct leakage is reduced through duct leakage testing and sealing strategies.
Tolerance for refrigerant charge variation	Equip units with a thermostatic expansion valve or provide diagnostic capabilities to self-monitor refrigerant charge level, and detect when the refrigerant charge is outside a preset limit. Refrigerant charge variations, gone undetected, affect the efficiency of the units.
Motor efficiency	Use NEMA-Premium motors on supply fans. Premium efficiency motors are cost effective due to long run times in commercial applications.
Thermostats	Include thermostats that provide the capability to schedule heating, cooling, and fan schedules independently, and allow independent scheduling of the fan operating (intermittent/continuous) mode. Provide a dedicated cooling stage for the economizer to achieve integrated compressor/economizer operation. Treatment of unit and thermostat as an integrated system will avoid some control misspecification problems.

Table 2. Summary Advanced Rooftop Unit Tier 2 Preliminary Specification

Provision	Description
Self-test modes	Provide the capability to independently test and verify the operation of compressors, economizers, fans, and heating system. This capability will allow service technicians to more efficiently troubleshoot systems in the field.
Service valve locations	Locate the high-pressure refrigerant port on the liquid line within two to three feet of the condenser to improve the measurement of subcooling and aid in refrigerant recovery. This feature will improve troubleshooting and serviceability of units in the field.
Refrigerant circuit labeling	Label liquid lines to indicate the appropriate circuit on units with multiple compressors and provide a sealable service access port on units with compressors located in the condenser fan plenum. The feature will improve the efficiency and effectiveness of the field test procedures.
Sensor signal override	Provide the capability to override sensor outputs in a manner that allows verification of the sequence of operation. This feature will improve troubleshooting and serviceability of economizer controllers in the field.
Sensor readout	Provide the capability of reading the value of all control sensors to assist in troubleshooting and calibration by allowing the technician to troubleshoot sensors without removing them from the system.
Fan drive efficiency	Use a direct drive or tooth-type belt drive equipped with an automatic tensioning system. This feature improves the efficiency and reliability of the supply fan drive system.
Fan efficiency	Specify minimum supply fan efficiency under realistic external static pressure criteria. Use 0.5 in W.C. in the development of the fan and unit efficiency ratings.
Fan power during ventilation mode	Supply continuous ventilation air during occupied periods at reduced fan power using multiple speed or variable speed fan motors interlocked with outdoor air dampers.
Fault detection	Detect failed temperature and/or enthalpy sensors (short or open circuit) by sending a fault signal to thermostat and/or energy management system. Sense economizer position and compare with expected value based on control logic and sensor values. Send a fault signal to thermostat and/or energy management system. Provide an occupant warning at the thermostat or EMS console with when a fault condition has been detected.

Industry Response

The preliminary specification and a briefing paper describing problems identified during the PIER/Institute study were given to the Air Conditioning and Refrigeration Institute (ARI) for comment. The ARI and representatives from four major member companies joined discussions on the specification at CEE meetings in Boston and San Francisco. Reactions to the specification content and approach were generally skeptical. The following list summarizes key comments from the ARI members present:

- Summary findings don't match their experience, and equipment is more reliable than the research indicates. Manufacturers tended to attribute in-field performance problems to improper installation, operation, and maintenance by building operators and contractors.
- Some felt that unit diagnostics and more robust equipment design were not necessary, and the problems would be detected and corrected during routine service and maintenance.
- Manufacturers emphasized that it would be very useful for them to be involved early in the research project to help formulate the research design and to be consulted throughout the research project, and for the finished work products to undergo peer review.

- Air flow results below 400 cfm per ton were not necessarily a negative finding, and manufacturers felt that an installed flow rate range of 300-375 cfm/ton was fine on a national level. Higher flow rates apply only to dry climates like California, which are not as concerned with removing moisture and the effect of flow rate on dehumidification.
- Some of the items on the specification, such as sensor life and accuracy requirements, need refinement.
- Manufacturers appeared to have a low acceptance of the research's results involving frequency of in-field problems and potential energy savings.
- Others noted that even if the estimates of energy penalties associated with the field problems may be inaccurate, manufacturers should consider that there may be some in-field performance issues with their equipment.
- Manufacturers prefer performance-based specifications to prescriptive specifications. They felt the specification was, in essence, telling them how to design their products and that industry is in a better position to formulate solutions to the problems. However, they acknowledged the lack of standardized testing protocols inhibits the development of performance-based specifications.

Installation and service contractors at the meetings, as well as utility program managers, with field stories regarding performance problems lent credibility to the issue of in-field performance and serviceability. Additional studies with similar findings also helped guide the discussion away from debating numbers and toward general agreement to look at areas of consensus. Attendees acknowledged the dialog created in this process has brought the matter to the attention of the manufacturing community and highlighted a need for investigation into the proposed solutions and continuing communication.

The ARI and industry members stated that a formal request asking for their input to the most feasible design solutions to agreed-upon problems would be addressed by their organization. One manufacturer said "no one has ever come to us asking us to solve these problems. If you ask, we will join you in the solutions." This proactive engagement with manufacturers resulted in the following benefits:

- Clearly raised the issue of reliability of performance to the major manufacturers in the U.S.
- Provided technical review and feedback on the past methods and outcomes .
- Demonstrated the need for multiple sources, documentation and testimony on problems of a product in order to establish credibility and gain support for potential solutions.
- Established a working relationship to reach agreement on core problems and possible solutions.
- Emphasized the value of testing protocols and performance-based solutions.
- Gained early participation by manufacturers in upcoming public research of lab and field testing potential solutions.
- Increased the understanding of the role, market influence, product development timeline and objectives of the participating parties (manufacturers, service contractors, public benefits and market transformation organizations, and utilities).

Next Steps

Although the early discussions were somewhat contentious, valuable guidance and benefits for next steps emerged from the dialog.

Based on the industry feedback, a memo was drafted to ARI from the CEE High Efficiency Commercial Air Conditioning (HECAC) Committee. The purposes of the memo were: 1) to identify the top priority problems with rooftop units, 2) to clarify the objective of the HECAC committee in addressing these problems, and 3) to engage the manufacturing community on how our industries could work together to accomplish the stated objectives. Criteria used by HECAC members in selecting the top problems included: frequency of the problem, energy impacts of the problem, variety of known potential solutions, and cost and ease of known potential solutions. The priorities listed in the memo were:

1. Economizer reliability and control
2. Impact of refrigerant charge variation on unit efficiency
3. Discrepancy between field and rating conditions for supply fan power
4. Systems and controls incompatibility
5. Field testing and serviceability

An ARI member has introduced the memo and the draft specification within the ARI Unitary Products Group and will provide committee feedback. CEE is continuing the dialog with ARI and its members in order to build a consensus solution to in-field performance problems.

In parallel with our effort to seek timely response from the manufacturers, continued research and testing of an advanced rooftop unit demonstration project based on the preliminary specification is being funded through PIER. The project will develop, test, and demonstrate an advanced packaged rooftop unit (ARTU) prototype of five-ton cooling capacity that addresses many of the in-field performance problems described here. Features of the ARTU will include improved outdoor air control, improved economizer reliability, diagnostics and troubleshooting capability, and fault-tolerant design. Detailed costs and benefits of each potential feature will be developed to help guide the final design of the demonstration unit.

During the course of this project, test protocols and rating methodologies will be investigated to facilitate the development of performance-based specifications. Active participation in this project by ARI members is expected.

Conclusions

Although solutions to these problems rest in the hands of market actors up and down the building design, construction, installation, and maintenance chain, we believe that manufacturers play a key role in the overall solution. Improving service and maintenance practices alone will not solve the problem[3]. By designing more reliable and serviceable equipment, the energy

[3] Interviews with HVAC service contractors (PECI, 2002) indicated that routine preventive maintenance generally involves only filter changes, coil "inspection," blower lubrication, and a cursory check of unit operation. Units generally are serviced only when they stop delivering cooling.

savings potential of small HVAC systems can be realized in a more cost-effective manner[4]. Manufacturers have a major role in the industry as suppliers of equipment and technical information to designers and contractors. Their leadership is seen as crucial to realizing the long-term energy savings potential of high-performance HVAC systems in small commercial applications.

Lessons Learned

The preliminary specification was a long list of features desired by many members of the HECAC committee. As such, it may have been too demanding to the manufacturers. The key issue moving forward is to jointly prioritize those issues that have the greatest potential impact and the highest potential for success. The PIER ARTU demonstration project will provide the opportunity to develop more detailed cost and benefit data to help the prioritization effort.

The manufacturing community clearly favors a performance-based approach where problems are identified through initiatives like the CEE HECAC program and the solutions are developed by industry. However, the timelines associated with a performance-based approach can be very long. According to manufacturers, product upgrade cycles can take 18 to 24 months and involve not only in-house engineering design but also interactions with suppliers who provide many of the unit components. One or two seasons of field-testing may be required once changes are made. Major redesign efforts can take five years or more, depending on the extent of the changes. Standards and test procedures may need to be developed and approved to verify that the redesigned equipment meets reliability goals. Other priorities, such as redesigning equipment for compatibility with new refrigerants, can compete with efficiency and reliability issues for research and development funding.

A specification approach such as our Tier 1 list focusing on key features available now in the marketplace can help improve reliability in the short run, and should be pursued in parallel with a more comprehensive performance-based approach. The key issues for our ongoing interactions are how to increase the priority of equipment-based solutions; how to manage participation but not obstruction; how to build trust and mutual understanding of the issues facing manufacturers, contractors and consumers; and how to shift the perception of this initiative from a perceived regulatory threat to a market opportunity.

Manufacturers have an opportunity to market "up sell" products to a market that is very first price conscious, with an opportunity for increased profitability. Many of the features promoted by the Tier 1 specification are already demanded by large chain accounts who understand the value of minimizing costs over the life of the equipment. Customers receive equipment that is inherently more reliable, increasing comfort while reducing energy costs. Increased serviceability allows HVAC service companies to do more effective service work within the constraints of the HVAC service market conditions, which is also very price conscious. Utilities realize a greater return from their investments in energy efficiency, as the energy savings from the HVAC units promoted through their programs is more persistent. Articulating these benefits and a strong interaction with manufacturers will be as critical as specific technical solutions to help make Advanced Roof Top Units available in the near future.

[4] Costs involved with field repairing economizers have caused some researchers to recommend disabling rather than fixing broken economizers under some conditions. See Felts (2000) and Lunneberg (1999).

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