HVAC Energy Efficiency

Maintenance Study

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Executive Summary

Research has shown that the performance of existing residential and small-commercial heating ventilating and air-conditioning (HVAC) systems is far from optimal. In many cases, the systems were never installed correctly and have never operated optimally, resulting in lower efficiency than implied by the nameplate rating. In other cases, the performance has degraded over time, either because of faults or improper service, causing the equipment to malfunction or to perform poorly. Measures such as duct sealing and repair, condenser and evaporator coil cleaning, refrigerant charge and air flow adjustments, economizer retro-commissioning, and HVAC controls can potentially produce significant savings.

The California investor-owned utilities (IOUs) have shown a great deal of leadership in initiating maintenance-based HVAC programs. These and other energy efficiency programs have been in existence since the 1980s, and have reached millions of homes and small businesses. Despite their success in reaching the market, however, the energy savings attributable to HVAC maintenance programs have been called into question. For example, one evaluation of savings for residential charge and air-flow adjustment programs in the 2006-2008 program cycle found quite low savings rates, but also found wide variations in the different program impact parameters. These studies raised the possibility that some of the Evaluation, Measurement and Verification (EM&V) questions being asked and answered have such large uncertainties that conclusions and recommendations based on them should be considered carefully.

In the long run, achieving the ambitious California Public Utilities Commission (CPUC) "Big-Bold" HVAC goal of 50% improvement in residential and small commercial HVAC system efficiency will require new, more comprehensive programs that have the potential for greater impact. For these programs to constitute a prudent use of ratepayer money, however, they must be designed based on a good understanding of the impacts and interrelationships of individual and combined system faults (i.e., abnormal conditions that may lead to system performance degradation or failure) and maintenance measures. A simple "widgets" approach that focuses on individual measures that save 10% here and 5% there will not achieve the level of savings that is needed to meet the CPUC's ambitious goal. HVAC technologies should benefit from a broad based systems approach.

Highlights of our analysis include the following key observations, each of which is discussed in depth in the report.

Uncertainties are inherent in programs such as these and are not well accounted for. There are many interrelated sources of uncertainty, including measurement errors, uncertainties in predicting human behavior, and the compounding effect of performing calculations on imperfect data. Perhaps the most important observation here is that, with the program specifications, methods, and tools commonly used *today*, it is difficult for a simple refrigerant charge adjustment to be implemented, measured, and verified to the level of confidence that is required by the CPUC. It is impossible to eliminate all sources of uncertainty, but they should be mitigated where possible (e.g. if the technician stops when a target superheat or subcooling value is reached there will be a 50% chance that the charge will be within the desired range, and a 50%

chance that it will not). A good understanding of uncertainties by program designers, contractors, and technicians is important.

Additional screening and more sophisticated diagnostic/servicing approaches would benefit future programs. Quality maintenance programs have the potential to be successful, but their design and structure could be improved. For example, if technicians perform basic screening of HVAC systems to determine whether (and which) services are likely to improve efficiency before implementing charge adjustments, additional energy could be saved. Furthermore, implementing multiple measures can potentially save much more energy than the current strategy of implementing single, simple measures, particularly when multiple faults are present. The costs of providing such a comprehensive service may be higher. However, the additional savings might justify the cost at a large number of sites. The presence of multiple faults and the need for multiple measures complicates diagnostic/service protocols in ways that are not well understood. There is not a thorough, up to date, and independent assessment of the baseline fault conditions of the over 10 million unitary air conditioners in California. Further study would help to develop appropriate diagnostic and service strategies that can be guided by the principles of making sure that no harm is done to the system, that energy efficiency is improved, and that to the greatest extent possible every site visit results in an energy efficiency improvement.

Human factors are significant but are poorly understood. The behavior, motivations, preparation, and constraints on technicians, owners, tenants, contractors, and EM&V specialists can make or break a program. This is an area that has been overlooked in the field of behavioral research, and a better understanding of why people do what they do is critical. If broad CPUC energy efficiency policy goals are to be achieved, the measurement of "free-ridership" needs to be improved to recognize that HVAC quality maintenance measures and services do not exist without the support of energy efficiency programs.

Measurement and verification processes must be improved. EM&V processes and instrumentation need to be improved and integrated with program delivery, quality control and reporting. One-time field EER measurements appear to be of marginal value since uncertainties can approach ±20%. Even with high-quality, time-series EER measurements, there is uncertainty in simulating the annual kWh savings, in part due to behavioral factors affecting occupancy and thermostat patterns. Longer term, broadly implemented pre- and post-measurements of kWh consumption would reduce uncertainty, and could be implemented using utility smart meters and/or web based sub metering.

Over the long term, achieving large energy savings might be possible with replacement of existing systems and integration with whole-building energy efficiency measures. Intuitively, the whole-building approach to energy efficiency should be much more effective than implementing energy efficiency measures in a piecemeal fashion, with the potential to achieve savings of over 50%. Past attempts at this approach have enjoyed limited success. The theory is that a new HVAC system can be sized for the reduced load that results from improvements in ducts, windows, insulation, lighting, infiltration, etc. Equipment kW savings are achieved, although kWh savings are less certain. In the long term, the HVAC industry and utility energy efficiency programs will continue to improve and will likely include providing quality installation, commissioning, automated diagnostics, demand response, and whole-building integration, in addition to maintenance. There will probably always be a need for maintenance-based programs to address the HVAC systems that can become efficient when they receive quality maintenance and the repairs that are needed.

In the short run, the authors feel that maintenance-based programs continue to be refined, improved, and redesigned. The focus of this study is on how the industry can be moved from current programs to better programs in the future. This project was sponsored by Southern California Edison (SCE), Pacific Gas and Electric (PG&E), San Diego Gas and Electric (SDG&E) and Southern California Gas (SCG) EM&V funds and managed by SCE to evaluate the current state of knowledge on the impact of HVAC maintenance measures, analyze potential sources of uncertainties, and develop recommendations for additional research. We hope this report will provide a common framework for discussion and facilitate better communication among program stakeholders, while providing insight into potential areas for improvement.

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1 Introduction

Energy use is increasing in California, with current projections indicating that by the end of the century household energy use will grow by as much as 55% in the hotter regions of the state[1]. Peak demand is also growing, resulting in the use of high-cost peaking power plants that operate only a few hours every year. Residential and commercial unitary HVAC units contribute significantly to peak demand, with residential units accounting for 24% of peak demand in 2006.[2] Before the widespread use of vapor compression cycle air conditioners the cooling peak did not exist or was small driven by use of circulating fans. Unitary air conditioners typically do not achieve rated efficiency because of improper installation or lack of servicing: lab testing suggests that service and replacement programs can yield energy savings on the order of 30-50%[3]. For these reasons, HVAC units have become a focal point for energy efficiency programs.

In 2006, Assembly Bill 2021 directed the California Energy Commission (CEC) to develop a "strategic plan designed to improve energy efficiency and reduce peak energy use of central air-conditioning systems in California." The CEC's strategic plan focused on new systems covered by Title 24, and on the building permit process. In September 2008, the California Public Utilities Commission (CPUC) adopted the California Long-Term Energy Efficiency Strategic Plan, referred to as the "Big-Bold" plan. The Big-Bold plan built on the CEC's strategic plan and envisioned a radical transformation of the residential and small commercial HVAC industry. The Big-Bold plan set very aggressive energy reduction targets: a "50% improvement in efficiency in the HVAC sector by 2020, and a 75% improvement by 2030."[4]

To achieve the goals of AB 2021 and the Big-Bold plan, there have been a number of HVAC-related energy-efficiency measures and incentive programs implemented in California. From 2006 to 2009 the CPUC approved and monitored a variety of Duct Test and Seal (DTS) and Refrigerant Charge and Airflow or Adjustment [5](RCA) service programs, which were administered by Investor Owned Utilities (IOUs). The DTS and RCA programs used estimated energy savings and estimated incremental measure costs to create incentive payment schedules.

There is controversy surrounding the question of whether the programs were cost effective when evaluated using ex ante (estimated before the program) deemed kWh/year savings based on the "Total Resource Cost Effectiveness" method.[6] Savings values based on Evaluation Measurement & Verification (EM&V) studies (ex post) were so low that the programs are not considered cost effective by the study authors. Experts in the field point out the necessity of distinguishing

[1] p. 13, Auffhammer, M., Aroonruengasawat, A., "Uncertainty over Population, Prices or Climate? Identifying the Drivers of California's Future Residential Electricity Demand," Energy Institute at Haas, WP 208, August 2010.
[2] p. 5, Messenger, M., "Strategic Plan to Reduce the Energy Impact of Air Conditioners," CEC-400-2008-010, June 2008.
[3] p. 20, Messenger June 2008.
[4] p. 58, Section 6, California Long Term Energy Efficiency Strategic Plan, California Public Utilities Commission, September 2008.
[5] Different interpretations of what "A" in RCA means. "Adjustment" is the technically accurate meaning since airflow is not measured but is determined to be adequate based on the temperature split. EM&V studies and some programs call out "Airflow".
[6] http://www.ethree.com/public_projects/cpuc4.html

between cost effectiveness of the measures and cost effectiveness of the programs that implement them on a broad scale.

The key EM&V studies are as follows:

- **August 2006 – EM&V Final Report, RCA Verification Program for New and Existing Residential and Commercial Air Conditioners; CPUC # 1385-04, 1395-04, and 1437- 04, CALMAC Study ID – RMA 0001.01; Aloha Systems.**

  The Refrigerant Charge and Airflow Verification Program (RCAVP) implemented by Robert Mowris & Associates is assessed. "The net energy savings achieved by the statewide program were … 113% of the energy savings goal … and 136% of the demand reduction goal …"[7] The program supported improvements in Title 24 RCA requirements. Participating contractors agreed with a report recommendation that the program should continue. The study was not designed to provide an assessment of measurement precision or confidence intervals and no field measurements were performed.

- **November 2008 – Residential Retrofit Contract Group First Draft Verification Report; CPUC Energy Division; The CADMUS Group.**

  An assessment of programs during implementation without final program results was performed by CADMUS. This study is used as an input to the February 2010 KEMA study. The report introduced Monte Carlo analysis of the probability of accurately measuring refrigerant superheat and subcooling. The study found that 47% of the duct sealing sites surveyed did not pass the program criteria[8] and 58% of the RCA sites surveyed failed. Concerns about the sample size and analytic methodology have been expressed.

- **March 2009 – Process Evaluation: CPACS Program 2007-2008; SCE0265.01; EMI**

  The report assesses the process and makes recommendations. A "Rapid-Feedback" evaluation was done in 2007 during the 2006-2009 implementation timeframe and then followed up beginning in mid-2008. This second assessment identified if and how the initial recommendations were addressed as well as any additional program performance issues."[9] Problems with planning, goals projection, and production meeting the goals occurred. Concerns about savings estimates, work papers, cost effectiveness calculations and the uncertainties of the VSP applied technologies led to the recommendation[10] that "SCE should coordinate with the other IOUs, California Energy Commission, CPUC, and

[7] p. I, EM&V Final Report, RCA Verification Program for New and Existing Residential and Commercial Air Conditioners; CPUC # 1385-04, 1395-04, and 1437- 04, CALMAC Study ID – RMA 0001.01; Aloha Systems. Robert Mowris Associates (RMA) is now Verified, Inc.

[8] Criteria are disputed by implementers as based on erroneous interpretation of the Duct Sealing program. Implementers claim that passing requires15% total leakage or a 15% reduction of total leakage. EM&V contractors only used 15% total leakage with no credit for reduction in leakage.

[9] p. 3, March 2009 – Process Evaluation: CPACS Program 2007-2008; SCE0265.01; EMI

[10] p. 5, EMI March 2009

verification service providers (VSPs) to quantify system and process uncertainties. These studies should lead to the development of processes or protocols that support improving the reliability of VSP field verification and ensure that measures are installed appropriately via post-installation review/inspection."

- **April 2009 – CPACS RCA Billing Analysis Report, EMI for SCE**

  In the Executive Summary the report concluded: "The billing analysis-based assessment of SCE's RCA measure showed no statistically significant energy savings for the general populations of participants studied (26 ± 28 kWh/year). The great difference between the confidence interval of expected savings found from this statistical analysis of participants' bills and the 2005 DEER calculated savings (233 kWh/year) provides a high degree of certainty that the DEER calculation requires re-calibration."[11]
  This analysis of billing data has been criticized as inappropriate because it does not follow the IPMVP guidance that "typically savings should be more than 10% of the base year energy use if they are to be separated from the noise in base year data"[12] when using billing analysis for measurement and verification. But, the California Energy Efficiency Evaluation Protocols do not include that guideline in the Gross Energy Impact Protocol.[13]

- **July 2009 – Market Assessment and Field M&V Study for Comprehensive Packaged A/C Systems Program, ADM Associates, SCE0286.01, July24, 2009**

  This study evaluated 109 units in the field and found that 89 had fault conditions, with 31 having two or more faults.[14] A rule-based diagnostic protocol adapted from work by James Braun and his colleagues at Purdue University was used to good effect: "The average EER for the units increased from 6.64 before servicing to 7.05 after servicing, an average increase of 6.1%. However, the results of a paired t-test showed that the hypothesis of "no difference" between the pre- and post-servicing averages can be rejected only with a confidence level of 80%."[15] Duct test and seal protocols and measurement techniques were included, and showed that airflow dropped when ducts were sealed for a group of 35 houses. Accuracy of instrumentation and uncertainty of EER calculations were not discussed and the sample size was limited. Finally, the protocol developed at Purdue is not universally accepted by experts in the field.

- **February 2010 – Evaluation Measurement and Verification of the California Public Utilities Commission HVAC High Impact Measures and Specialized Commercial**

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[11] p. 1, CPACS RCA Billing Analysis Report, EMI for SCE, April 2009.
[12] p. 28, International Performance Measurement & Verification Protocol Concepts and Options for Determining Energy and Water Savings Volume I, DOE/GO-102002-1554, March 2002.
[13] p. 28-30, California Energy Efficiency Evaluation Protocols: Technical, Methodological, and Reporting Requirements for Evaluation Professionals, Prepared for the California Public Utilities Commission by The TecMarket Works Team,April 2006.
[14] p. 4-9, ADM July 2009
[15] p. 6-1, ADM July 2009

Contract Group Programs, 2006-2008 Program Year, Volume 1, KEMA, CADMUS and Summit Blue, CPUC, February 10, 2010 and Volume 2, Appendices.

Refrigerant Charge and Airflow (RCA) and Duct Test and Seal (DTS) were two of the high impact measures covered by the study that considered them as contained in programs administered by the IOUs. The estimated savings, or ex post savings estimates, were so much lower than normally encountered in EM&V studies that the validity of the programs has been challenged. In Table 3-1[16], of the nine programs studied, the best had an ex post that was 45.6% of ex ante and the worst was at just 5% (weighted average of 20.1%). In Table 3-5[17] of the five DTS programs the worst ex post was 26.5% and the best was 49%. With over half of the savings coming from the worst program the weighted average was only 29.8%. The study did not attempt to measure the annual kWh savings. Ex ante deemed savings were significantly reduced due to finding low rates of proper installation and higher than expected free ridership. A Monte Carlo technique was used to compare the uncertainty of HVAC contractor superheat and subcooling results with the findings of the EM&V team. But, there were no uncertainty estimates given for the EERs that were calculated from field measurements. The study was also burdened by lower than planned sample size. There is an intense controversy about the validity of the study that is not the focus of this report but that is indicative of the uncertainty that surrounds HVAC Quality Maintenance (QM) programs.

Taken together, these six EM&V studies raised serious questions about the design and efficacy of the implementation of current DTS and RCA energy efficiency measures. For this reason, as of August 2010, the California IOU's HVAC Quality Management programs are largely on hold, with many demand-side management (DSM) experts being concerned about their viability. A few third-party programs (which make the implementer more responsible for achieving the predicted energy savings, rather than the IOU) are still active but the mass market SCE core programs for 2010 do not include the RCA and DTS programs of 2006-2009. PG&E and SDG&E presently offer scaled down revised RCA and DTS programs. Pressure is building to get programs restarted as soon as possible, but only with a good understanding of how to improve them to ensure their effectiveness. While it may not be possible to arrive at consensus among the stakeholders, it could be beneficial to convene a forum for the purpose of forging consensus. The forum would be successful if it clearly defines areas of disagreement, areas needing more research and how to get the work done. For example, the problems of small field sample size and the paucity of detailed field test data are widely recognized as a high priority issues.

It's unclear whether the current programs' disappointing results were due to ineffective program design, overly optimistic projections, or inaccurate pre- and/or post-implementation evaluation techniques. What is clear is that the DSM industry needs a sound strategy for designing programs and evaluating their effectiveness.

During this same time frame a set of four national consensus standards were adopted and published. The concepts of quality maintenance (QM) and quality installation (QI) are clarified

[16] p. 13,Volume 1, KEMA February 2010
[17] p. 16, Volume 1, KEMA February 2010

by the standards and are utilized by this report. Without the QM standards, RCA and DTS stand alone as energy efficiency measures. With QM standards, RCA and DTS are integrated into HVAC contractor business practices while raising new questions about how to handle levels of QM that progress from simple service activities, to complete diagnostics, to adjustments, and finally to recommendation of repairs. Discussion at the August Technical Forum and elsewhere points to stakeholder concerns that the standards are too complicated and will be generally too costly to be implemented.

The four standards that influence HVAC maintenance are:

1. ACCA Standard 4: In 2008, ACCA published ACCA Standard 4: "Maintenance of Residential HVAC Systems" (ANSI/ACCA 4 – 2008). This standard includes a set of screening tasks that could form the basis for a maintenance program.

2. ACCA/ASHRAE Standard 180: In 2008, in support of commercial system screening, the following ANSI/ASHRAE/ACCA Standard 180 – 2008 was approved: "Standard Practice for Inspection and Maintenance of Commercial Building HVAC Systems." This standard covers the full range of commercial equipment. A proposed Economizer Table developed by the Western HVAC Performance Alliance is being considered for inclusion.

3. ACCA Standard 5: In 2007, the Air Conditioning Contractors of America (ACCA) published Standard 5: "HVAC Quality Installation Specification" (ANSI/ACCA 5 QI – 2007). This standard covers the installation of air conditioners and ducts, and emphasizes duct quality.

4. ACCA Standard 9: In 2009, ACCA published Standard 9 (ANSA/ACCA 9 QIVP – 2009): “HVAC Quality Installation Verification Protocols” which sets forth the procedures for verifying adherence with Standard 5.

2 Project Objectives

In the aftermath of the recent EM&V studies, fundamental differences of opinion have emerged on what, if anything, went wrong with previous programs (and why), and on how to move forward with future energy efficiency programs. In this report, we hope to provide a common framework for discussion and to facilitate better communication among program stakeholders, while providing insight into potential areas for improvement. It is impossible to eliminate all sources of uncertainty -- whether they are in measurement and analysis or human behavior -- but it is critical to design programs with a better understanding of the sources of uncertainty and their potential impacts. With this in mind, the key objectives of this project were to:

1. Assess the current state of knowledge about the impact of unitary HVAC equipment maintenance measures, including potential savings and long-term persistence of these savings. The technical focus is on the efficiency of the cooling

system (i.e., the refrigeration and duct systems) and not on the heating and ventilation systems.

2. Identify key uncertainties that affect the energy and demand savings potential of these measures, and that affect the ability to measure these savings.

3. Assess current information on the roles of these uncertainties in reducing the savings from these measures.

4. Propose research activities to help fill in the gaps in our understanding of factors affecting savings.

This project is not intended to provide a complete analysis and critique of current measurement and diagnostic procedures or program designs. Instead, our focus is on developing the next steps that will lead to better program design and implementation resulting in verified savings.

3 Methodology

A project of this nature is challenging since there are many stakeholders and a broad range of issues to be addressed, ranging from technical details to broad CPUC policy goals. There is significant interplay between technical issues (e.g., sensor installation procedures) and human factors (e.g., how the contractor directs the technician to implement the program requirements). This project was designed to better understand the issues related to uncertainty and EM&V issues and to develop a roadmap to provide direction on future research and program needs.

The following activities were conducted in this study:

- Assembled and developed a summary review of key publications and reports over the past 20+ years that provide a basic catalog of information relevant to HVAC energy efficiency.
- Analyzed laboratory test data from HVAC systems operated with and without faults.
- Worked with verification service providers (VSPs) and the EM&V contractors to better understand their processes, quality control procedures, and diagnostic protocols.
- Assessed implementation of VSP processes in the field.
- Utilized the knowledge and perspective of an experienced refrigeration engineer in reviewing current VSP procedures, sensor specifications, identification of multiple faults, etc.
- Interviewed stakeholders, industry experts, and diagnostic equipment manufacturers to gather input on data collection procedures, calibration issues, and measurement repeatability.
- Incorporated fundamental analysis of uncertainty statistics in better understanding how program specifications need to be set to ensure that a meaningful result is generated.
- Gathered input from utilities, industry groups (such as the Western HVAC Performance Alliance), VSP's, and researchers.

In this project, we did not delve into the databases generated by the VSPs in the process of tracking the delivery of the 2006-09 programs; this work has been done by others. Instead, we focused our efforts on the programs' technical foundations.

As the project evolved over the past seven months, it became increasingly clear that it would be critical to solicit stakeholder input and work towards consensus building in order to keep HVAC maintenance focused programs moving forward. To that end, we organized and facilitated two meetings that brought together a wide range of industry stakeholders. The first was a day and a half Tech Forum held at PG&E's Stockton Training Center on August 4th and 5th, 2010. The second was a mid-August informal session held at ACEEE's biennial Summer Study, titled "Unitary HVAC Quality Maintenance Project: Fault Detection, Diagnostics and Repair; and Duct Test and Seal". Input from the meetings has been integrated into this report.

The Davis Energy Group team was comprised of Project Manager Marshall Hunt, PE; Marc Hoeschele, PE; Beth Weitzel; Bill Dakin, PE; and David Springer. The Western Cooling Efficiency Center effort was lead by Kristin Heinemeier, Ph.D., PE. To assist the core consulting team, a small group of outside consultants were added to the team to provide additional expertise. These consultants included:

- **Allen Amaro, Amaro Construction.** Mr. Amaro is a practicing HERS rater who completes RCA inspections under current Title 24 processes.
- **Jennifer White** provided technical writing and editing.
- **Mark Cherniak, New Buildings Institute.** Mr. Cherniak is the Senior Program Manager with New Buildings Institute, and has over 25 years of experience in the field of energy efficiency.
- **Jim Phillips, The Energy Savers.** Mr. Phillips has over 45 years of hands-on and training experience in the HVAC industry working on both residential and commercial systems and is a NATE certified technician.
- **Dr. Neil Willits, UC Davis Statistics Lab.** Dr. Willits provided support in understanding the statistical basis of measurement uncertainty.
- **Hugh Henderson, PE, CDH Energy.** Mr. Henderson contributed to the discussion of normalization in Section 6.
- **Campbell BrownKorbel.** Ms. BrownKorbel provided writing and editing skills.

The project also convened a Project Advisory Panel (PAP) to provide review input to the team on key deliverables. The panel was selected from HVAC industry leaders with a broad range of expertise. Participating PAP members included:

- **Edward Vine, Lawrence Berkeley National Labs (LBNL).** Dr Vine is a Staff Scientist at LBNL and is the Manager of the Environmental Program at the California Institute for Energy and Environment (CIEE).
- **Mike Lubliner, Washington State University (WSU).** Dr. Lubliner is a researcher at WSU and co-chair of the ASHRAE 6.3 Residential Central Forced Air Heating and Cooling Equipment committee.

- **Loren Lutzenhiser, Portland State University (PSU).** Dr. Lutzenhiser is a Professor of Urban Studies and Planning at PSU with a focus on behavioral studies related to energy and water use.
- **Hugh Henderson, CDH Energy.** Mr. Henderson has an extensive background in the monitoring and modeling of unitary HVAC equipment.
- **Piotr Domanski, National Institute of Standards and Technology (NIST).** Dr. Domanski is the HVAC&R Equipment Performance Group Leader at NIST.
- **Marc Newman, Standard Refrigerators Inc.** Mr. Newman is President of a firm that provides design, installation, and HVAC service to commercial and residential customers in New York City.
- **Jim Braun, Purdue University**. Dr. Braun is a professor in the School of Mechanical Engineering and has worked in the field of air conditioning and refrigeration for over 30 years in both university and industrial settings.
- **Adrienne Thomle, Honeywell, Inc.** Ms. Thomle is a Product Market Manager of Economizer Systems & Motors at Honeywell.

A draft of this study was circulated to stakeholders for review and many substantive and helpful comments were received. All substantive comments were carefully considered and changes have been made for this final draft. Out of respect for input from stakeholders and in the interest of transparency, footnotes are used to give credit to sources that are not in published documents. This allows the report to be current. Care was taken to ensure that the comments came from legitimate sources. Given the controversial nature of the subject and the need for more research, reasonable experts disagree. This report takes note of the disagreements but does not try to make final judgments as to who is right and who is wrong.

4 Refrigeration Cycle Analysis and RCA Programs

The refrigeration cycle is a complex thermodynamic process that is well understood in a laboratory setting resulting in the design and production of high-quality systems of increasing sophistication. Despite the fact that several studies of field performance have been done[18,19,20,21,22,23,24], field problems are still not as well understood as lab performance, given the wide

[18] Davis, R. 2001. "Influence of Expansion Device and Refrigerant Charge on the Performance of a Residential Split-System Air Conditioner using R-410a Refrigerant," Report No.: 491-01.7. San Francisco, Calif.: Pacific Gas and Electric.

[19] Downey, T., Proctor, J., 2002. "What can 13,000 Air Conditioners Tell Us?" Proceedings of the 2002 American Council for an Energy Efficient Economy Summer Study on Energy Efficiency in Buildings.

[20] Li, H.. "A decoupling-based unified fault detection and diagnosis approach for packaged air conditioners. Ph.D. Thesis, West Lafayette, IN: Purdue University," 2004.

[21] Farzad, M., O'Neal, D. 1993. "Influence of the Expansion Device on Air Conditioner System Performance Characteristics Under a Range of Charging Conditions." Paper 3622. ASHRAE 2004 ACEEE Summer Study Proceedings I-226 Transactions. Atlanta, Ga.: American Society of Heating Refrigerating and Air-Conditioning Engineers.

[22] Rodriguez, A., "Effect of Refrigerant Charge, Duct Leakage, and Evaporator Air Flow on the High Temperature Performance of Air Conditioners and Heat Pumps," Master's Thesis, August 1995.

[23] Siegel, J., Wray, C., "An Evaluation of Superheat-Based Refrigerant Charge Diagnostics for Residential Cooling Systems," ASHRAE TRANSACTIONS 2002, V. 108, Pt. 2.

variety of installation issues, occupant impacts, improper service over time, and component degradation which contribute to a large degree of performance uncertainty. This section provides an overview of refrigeration system operation and performance issues, along with an analysis of current RCA program specifications and challenges.

Figure 1 illustrates the key components of a unitary refrigeration system[25]. These components (compressor, condenser, evaporator, expansion device, fans, and controls) are generally separate in residential systems (split system with indoor and outdoor equipment), and typically "packaged" for commercial rooftop units (RTUs). The numbers in Figure (1-4) refer to the four system states: 1) low pressure, cool vapor; 2) high pressure, hot vapor; 3) high pressure, warm liquid; and 4) low pressure, cold liquid that in turn becomes vapor again after the evaporator coil. Outdoor air cools the hot refrigerant gas at the condensing unit, causing the refrigerant to change phase from gas to liquid. The liquid refrigerant is forced through the expansion device (orifice or TXV) at which point the low pressure causes a fraction of the liquid to "flash" to vapor. At the indoor coil (evaporator), warm return air causes the rest of the liquid refrigerant to change to a gaseous state. During this phase change process, the return air is cooled at the evaporator, typically on the order of 18-22 °F. The low temperature refrigerant gas then enters the compressor where mechanical work raises the pressure and temperature of the gas.

[24] Temple, K., Rossi, T., Field Diagnostics Services, Inc., "Enhanced Refrigeration Diagnostics for an Improved Air Conditioning Tune-up Program," ACEEE Summer Study, 2006Mowris, R., Blankenship, A., et. al, "Field Measurements of Air Conditioners With and Without TXV's," ACEEE Summer Study Proceedings 2004.
[25] Figure adapted from EES, http://www.fchart.com/ees/

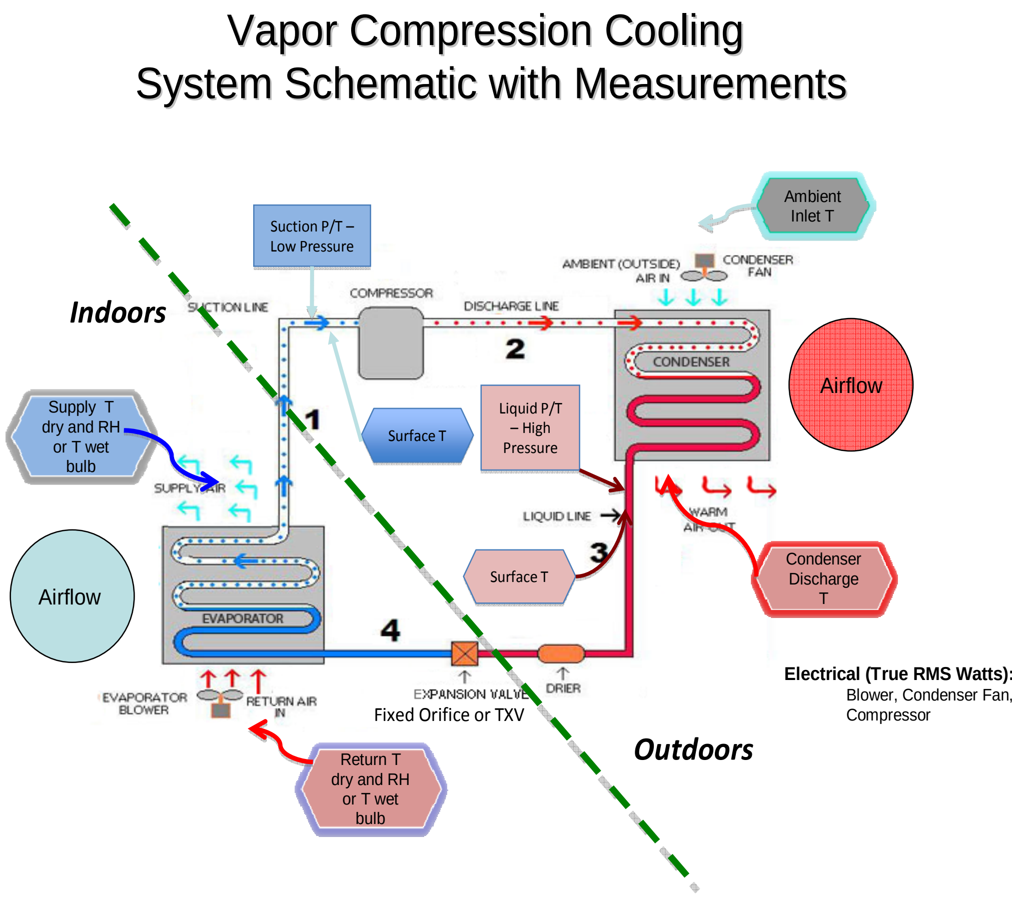

Figure 1. Unitary Refrigeration System Schematic.

A key challenge in understanding refrigeration system performance is that there are many possible sources of degradation, some of which are more significant than others, and there is rarely an obvious indication which part (or often, parts) of the system is failing. Furthermore, there is a wide range of system performance characteristics encountered in the field which depend on ambient conditions, the load on the evaporator, and the fault status. In spite of the complexity of multiple faults and highly variable performance, HVAC technicians providing service calls are expected to improve system efficiency, often within a short scheduled time window. A systematic approach is needed to fully assess the current state of any HVAC system in the field. The flow chart shown in Figure 2, adapted from Dr. Haorong Li's dissertation on addressing multiple system faults[26], illustrates the “taxonomy” of faults in an existing unitary HVAC system.

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[26] p. 49, Li, Haorong, "A Decoupling-Based Unified Fault Detection and Diagnosis Approach for Packaged Air Conditioners," PhD Thesis, Purdue University, August 2004.

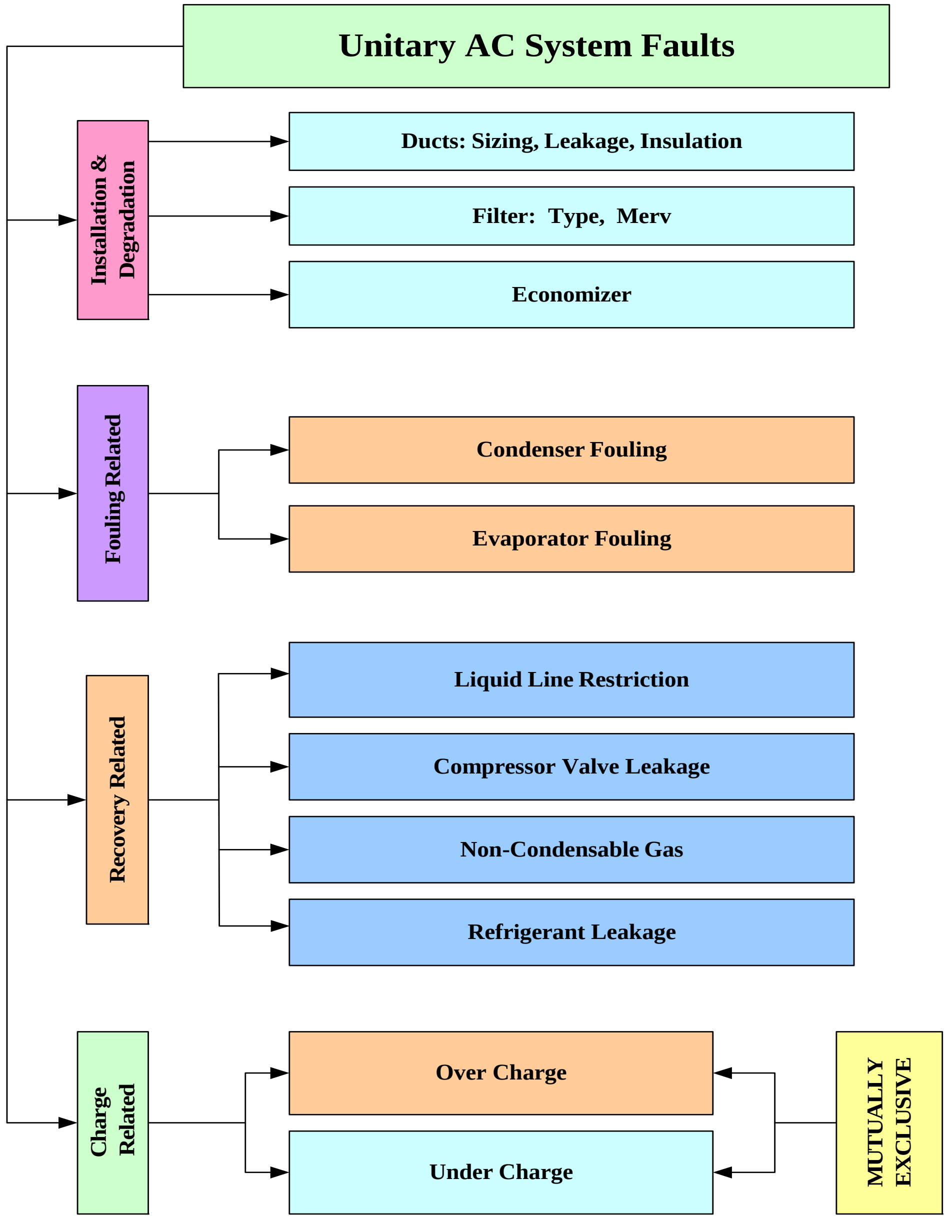

Figure 2. Taxonomy of Refrigeration System Faults

Multiple, simultaneous faults are possible, although some faults are insignificant and can be ignored. The extent of the problem with multiple faults is not well described in the literature, and experts disagree on the importance of multiple faults. Fortunately, there are commonly encountered faults such as coil fouling, contactor failure, capacitor failure, and, in the case of commercial RTUs, economizer failure that reduce the range of possible faults to a more workable list. A baseline study would serve to establish the range and distribution of fault conditions. Technicians ideally need a hierarchical screening process that starts with an assessment of installation and degradation, continues with visual inspections, and eventually addresses refrigerant charge. The process must be fast and cost effective. A technician in a comprehensive maintenance program, or a diagnostic system directing the technicians' efforts, would need to be able to do all parts of the screening and not just the charge-related items. Such a system needs to save time while minimizing misdiagnosis.

This process is complicated by the fact that technicians often do not have remote access to manufacturer data specific to the system, which would save time and potentially improve the accuracy of the diagnosis. Examples of data from manufacturers are: compressor performance map; superheat values; subcooling values; rated EER; blower performance; amperage draw for various components; charge for weighing in with long line adjustments; fault codes; and wiring diagrams. Some of this data is on the equipment or in a document that is intended to be left with the unit but, especially on older units, the data is missing. Service is competently done everyday without complete information but this is not the preferred situation. Energy efficiency programs add the challenge of optimizing system energy efficiency, which is not standard practice for technicians who often lack the training and instruments required to perform the necessary tasks.

4.1 RCA Program Issues

In past RCA programs the only service required to be performed was to check and adjust the refrigerant charge after verifying the supply airflow[27] across the evaporator coil is adequate. Some VSPs require their contractors and technicians to do more than the program minimum and require that technicians are competent to do the complete range of service functions. The charge is checked by considering only one of a half dozen key indicators of refrigerant cycle performance.

Other factors such as condenser and/or evaporator coil fouling (as shown in Figures 3 and 4) have significant impacts on system efficiency and whether the charge is correct. Figure 3 shows an extreme example of a residential condenser coil fouling from lawn clippings[28], followed by pet hair and dirt.

Figure 3. Condenser Coil Fouling

[27] Using the "temperature split" method (difference between supply and return air temperature)
[28] Image from http://desertcomfortmechanical.com/air_conditioning_repair_and_maintenance

Figure 4 shows heavy evaporator coil fouling[29], which is most common on systems with floor (or low wall) returns, especially in homes with cats and dogs. It can be difficult if not impossible for technicians to access and clean evaporator coils; contractors report having to cut access holes when none are provided. A VSP estimates that less than 1% of residential split system evaporator coils are accessible and that "only 0.4% of the evaporator coils get cleaned" even when there is a $40 incentive available[30]. There are various spray products that work with condensate to clean and wash away debris on the evaporator coil. Technicians need a simple diagnostic to determine whether either coil needs to be cleaned and then a procedure that instructs them on how to clean coils as part of QM servicing. Without this guidance it is possible for a program to "devolve from a comprehensive program to a condenser coil cleaning program only"[31].

Laboratory tests[32] conducted on systems with condenser and evaporator coil blockages have shown that coil blockage has a significant impact on system performance, with condenser airflow blockage having more of an impact than evaporator coil blockage at the same level of blockage. Evaporator fouling is more commonly found because, especially in residential split systems, the time and expense needed to properly clean them is prohibitive. In the lab, blockage is simulated by reducing airflow with panels. In the field, fouling not only blocks airflow but also coats coil surfaces, changing the heat transfer characteristics. The relationship between lab tested blockage and coil fouling in the field has not been established. Newer, high efficiency air conditioning units typically have narrower evaporator coil fin spacing, making it easier for coils to foul and harder to clean. As seen in the picture, a wet coil makes a very effective filter.

Figure 4. Evaporator Coil Fouling

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[29] Image from http://losangelescountyheating.com/
[30] PEG comments on 112310 Study Draft submitted to Brett Close, SCE.
[31] PEG comments on 112310 Study Draft submitted to Brett Close, SCE. The condenser approach temperature could be used and is straight forward to implement.
[32] Faramarzi, R., Rauss, D., "An Experimental Approach to Quantify Effects of Common Maintenance Strategies for 5-Ton Rooftop Units," ASHRAE 2010 Annual Meeting – Orlando Seminar 6 (Sponsored by TC-8.11) January 24, 2010, Technology Test Centers (TTC) Southern California Edison www.sce.com/rttc

Airflow evaluation needs to involve more than just making sure that the temperature split (difference between supply and return air temperature) is within a reasonable range. The Duct Test and Seal (DTS) programs require total duct leakage be reduced so that it is equal to or less than 15% of total flow with the assumption that there is 400 cfm/ton of air conditioner capacity. This in line with Title 24 2008 requirements implemented in the "**Simplified Prescriptive Certificate of Compliance: 2008 *Residential HVAC Alterations* CF-1R-ALT-HVAC"** form[33]. If a duct system is undersized sealing the leaks can reduce the airflow to the extent that the temperature split is significantly changed. RCA and DTS programs have not been linked allowing the RCA technician not to be concerned with leakage and the DTS technician not to be concerned with airflow. While direct measurement of airflow through the evaporator coil is allowed as an alternative to the temperature split test, this method is rarely done Measuring airflow with a flow metering plate[34] is slowly gaining acceptance in residential applications but contractors and technicians are resistant because of the cost of equipment and the time that it takes to make the measurement.[35]

4.2 RCA Program Specifications

Using laboratory data,[36] Title 24 RCA testing specifications[37], and the results of field research[38] the Architectural Energy Corporation (AEC) developed the "Technical Specifications and Best Practices for Charge and Air Flow Verification Services"[39] for the Pacific Gas & Electric Company (PG&E) that were used by the IOUs for the 2006-2009 RCA and DTS programs. The specifications provided for qualified VSPs to sign contracts with IOUs and gain approval to implement the RCA program. Technicians are required to have a US EPA refrigerant handling certification and training "including but not limited" to the following:

- Customer interaction
- Equipment calibration procedures
- Test procedures
- Data collection procedures
- Calculation and/or procedures required to determine pass-fail test status
- Charge and airflow correction procedures.

Measurement equipment requirements are focused on hand-held devices and the manual recording of readings in the field. Existing California Title 24 RCA procedures are used for the

[33] pdf page 450 of 563, California Energy Commission, 2008 Building Energy Efficiency Standards Residential Compliance Manual, CEC-400-2008-016-CMF-Rev1, March 2010.
[34] http://www.energyconservatory.com/download/trueflow.pdf
[35] PEG comments on 112310 Study Draft submitted to Brett Close, SCE.
[36] Davis, R., D'Albora, E.. "Influence of Expansion Device and Refrigerant Charge on the Performance of a Residential Split-System Air Conditioner using R-410a Refrigerant" Report No.: 491-01.7. San Francisco, Calif.: Pacific Gas and Electric, 2001.
[37] Appendix RD, Residential Alternative Calculation Method (ACM) Approval Manual for the 2005 Building Energy Efficiency Standards, CEC 400-003-003F, October 2004. Reference is also made to manufacturer (e.g. Carrier, Lennox, and Trane) guidelines as the source for the T24 methodology.
[38] Downey, T., Proctor, J., 2002. "What can 13,000 Air Conditioners Tell Us?" Proceedings of the 2002 American Council for an Energy Efficient Economy Summer Study on Energy Efficiency in Buildings.
[39] Residential Air Conditioner Charge and Air Flow Verification Study, Task 4 Report, Technical Specifications and Best Practices for Charge and Air Flow Verification Services, Contract # 4600010737, Revision 2, Architectural Energy Corporation, for PG&E, August 19, 2004.

purpose of determining whether the refrigerant charge is adequate, and if not, for adding or removing charge to achieve the required superheat or subcooling, as per program requirements. Unstated in AEC's specifications for the RCA program is the assumption that other HVAC system faults are either not present or are not impacted by the charge adjustment and that they do not eliminate the savings achieved by charge adjustment. RCA procedures follow the Title 24 guidelines which in the 2008 version use Table RA3.2-3 Target Temperature Split which covers return air dry-bulb conditions from 70 °F to 84 °F paired with return web-bulb conditions from 50 °F to76 °F. For superheat determination there must be at least 5 degrees. Referring to Table RA3.2-2 Target Superheat[40] if the outdoor temperature is below 65 °F then the indoors must be at least 70°F. The table goes down to an outdoor temperature of 55 °F with an indoor return wet bulb of 50 °F which can be done so long as the return dry bulb is 70 °F. These limitations have proven to be a problem especially when RCA work is done before and after the summer season. Outdoor temperatures up to 115 °F are allowed but over 100 °F require return wet-bulb temperatures that can be difficult to reach in hot dry climates.

Temperature Split: Table RA3.2-3 is used to look up the required temperature split based on the operating conditions, and the measured value must be within ±3 degrees of the reference value listed for the airflow to be considered adequate. The temperature split test does not measure airflow or ensure that at least 350-400 cfm/ton is flowing through the evaporator.[41] It establishes that there is an adequate balance between the quantity of refrigerant flowing through the evaporator coil, changing phase from liquid to gas as heat is absorbed, and the quantity of air flowing across the evaporator coil[42] that is being cooled be the refrigerant phase change.

Superheat: If a fixed orifice refrigerant expansion valve is used the superheat is calculated to determine adequate refrigerant charge. Superheat is based on measuring the pressure of the suction line and the surface temperature of the suction line. Fixed orifice (FO) expansion valves come in a variety of forms, none of which change size in response to operating conditions. Refrigerant mass flow rates do however vary in response to the pressure dynamics as driven by conditions at the evaporator and condenser. Charging is based on achieving the correct amount of superheat given the indoor and outdoor conditions and the value is found in Table RA3.2-2. The charge is considered correct if the superheat is within ±5 °F of the target value found in the Title 24 superheat table. Each refrigerant type has a temperature/pressure relationship that converts a pressure reading to the matching temperature, as shown in Table 1.

[40] pp. RA3-18 to RA3-20, California Energy Commission, Reference Appendices for the 2008 Building Energy Efficiency Standards for Residential and Nonresidential Buildings, CEC-400-2008-004-CMF, December 2008.
[41] Metoyer, J., Swan, E., McWilliams, J. "HVAC Airflow Measurement Issues for Programs and Evaluators," KEMA, 2010
[42] It is possible to reduce refrigerant flow and airflow in tandem to achieve the desired temperature split while reducing the capacity of the system.

Measured Suction Line Pressure (psig)	Saturation Temperature (°F) (Lookup at Measured Pressure)	Measured Suction Line Surface Temperature (°F)	Calculated Superheat (°F) (Measured Surface minus Saturation)
68.5	40	60	20
76.0	45	58	13
84.0	50	64	14
92.6	55	58	3

Table 1. Example R-22 Superheat Calculation

Subcooling: When a thermal expansion valve (TXV) is present, subcooling is calculated to assess whether the refrigerant charge is correct. A TXV has a sensing bulb attached to the refrigerant line exiting the evaporator coil. The sensing bulb is charged with a gas whose expansion and contraction in response to pipe surface temperature results in modulating the TXV valve, thereby adjusting refrigerant flow. A TXV is sometimes referred to as a constant superheat valve. Manufacturers specify the subcooling value for the system, but when it is not easily available; a default of 10 ^oF is often used even though manufacture values will vary widely with little impact on EER, making it a useful default value. Given the discussion at the Technical Forum it would be good to explore this issue further. The charge is considered correct if the calculated subcooling is within ±3 ^oF of the target value. But, as shown in Figure 5 in lab testing on two systems, in support of proposed Title 24 changes, "efficiency varied less than 5% over a range of subcooling from 2 ^oF to 21 ^oF"[43]. This testing and other testing being done at Intertek in 2010 could have significant impacts on our understanding of how to implement refrigerant charge correction measures.

[43] PEG comments on 112310 Study Draft submitted to Brett Close, SCE from "Measure Information Template – Residential Refrigerant Charge Testing and Related Issues", 2013 California Building Energy Efficiency Standards, California Utilities Statewide Codes and Standards Program, December 2010.

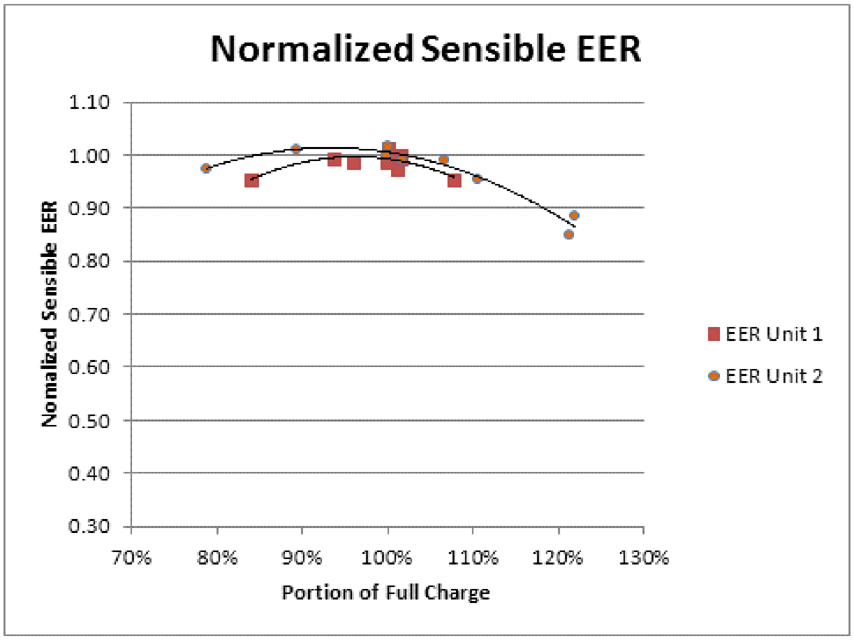

Figure 5. Variance of Normalized Sensible EER v. Subcooling

The process steps that a technician is required to follow are detailed in Sections 2.4.3 Non-TXV and 2.4.5 TXV.[44] The temperature split must be corrected before charge can be checked and adjusted as required. In the case of systems that are far from having correct charge and airflow a sequential approach does not work. Rather, the technician must iteratively adjust airflow and charge. Both the airflow and charge must be re-tested until they both sequentially pass."[45] Direct airflow measurement is allowed but not required. Coil, either evaporator or condenser, cleaning is not addressed. Filters are to be considered if the temperature split is high. While this approach makes sense for new equipment covered by Title 24, it ignores the "as found" condition of air conditioners if only the program minimum requirements are met. In some applications filters must be changed monthly and condenser coils cleaned quarterly.

Referring back to the taxonomy of fault conditions it is the case that if a technician is only doing the minimum by the RCA program specifications then only charge is checked. All that is needed is to have indoor and outdoor conditions within a broad range of conditions and the machine capable of running for 30 minutes producing air that is cooled about 20 degrees across the evaporator coil. This is a simplification of the complex operation of an air conditioner. It allows narrowly trained technicians to perform the RCA service quickly without regard to the multiple fault conditions that may be found in many systems. The complexity of the interactions is best illustrated by Figure 6 from H. Li[46]. Only a few of the possible faults on the left hand side impact just one component in the system and refrigerant charge, either high or low, impacts all of the components.

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[44] p. 8 – 12, Architectural Energy Corporation, Residential Air Conditioner Charge and Air Flow Verification Study, Task 4 Report, Technical Specifications and Best Practices for Charge and Air Flow Verification Services", Contract # 4600010737, Revision 2, PG&E, August 19, 2004.

[45] p. 11, AEC Task 4, 2004.

[46] p. 51, H. Li, 2004.

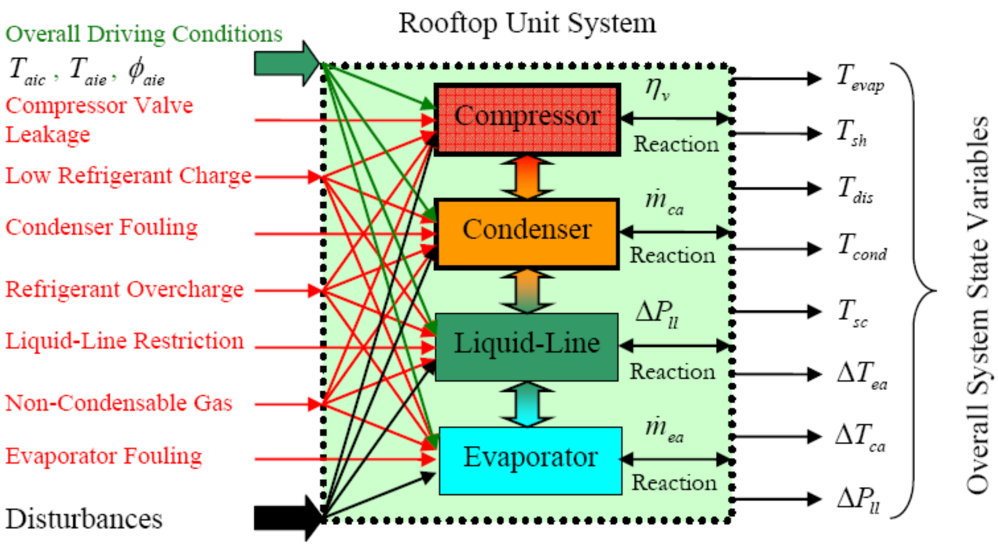

Figure 6. Complex RTU System Interactions

There is no consensus as to how to address multiple faults. In reviewing comments on this report, Field Diagnostic Services Inc. noted the following:

> Using the charging chart to calculate the superheat goal or comparing the subcooling to the manufacturer's specification are an implied "no fault" model of expected performance. A "no fault" model that predicts the evaporating temperature and condensing temperature over ambient goal values for a system of a specific design under specific driving conditions is essential to evaluating the complex operation of an air conditioner. Resolution of faults and degradations that impact evaporating temperature and condensing temperature over ambient is essential prior to charge adjustment based on superheat and subcooling.[47]

Comments from Proctor Engineering Group caution that it is not practical or necessary to resolve all faults. The RCA service "does not claim to be able to diagnose all possible faults, but it does diagnose the most common faults that have a significant impact."[48] We did not find adequate field test data to definitively settle this difference of opinion even though such a research study would be valued by all stakeholders.

5 Duct Systems and DTS Programs

The performance of residential duct systems has been extensively tested over the past 20 years with numerous studies[49] documenting the inefficiencies associated with ducts outside of conditioned space, such as those located in attics. Total duct leakage levels of 35-40% of system fan flow (at 25 Pascal pressure or 0.1 IWC) are fairly common in these prior studies. Duct leakage results in significant system inefficiency due to reduced space conditioning capacity,

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[47] FDSI comments on 112310 Study Draft submitted to Brett Close, SCE.
[48] PEG comments on 112310 Study Draft submitted to Brett Close, SCE.
[49] See: Kinert 1992, Palmiter and Francisco 1994, Jump 1996, Coito 1998, Lerman 1998, Walker 1998, Modera 1992.

with resulting peak demand impacts. The Duct Test and Seal programs implemented during the 2006-2008 time period were designed to reduce leakage in existing systems to 15% of total airflow or to reduce leakage by 15% of total system airflow. Duct pressurization tests were required before and after sealing with the results being reported to the VSP overseeing the contractor's work.

According to the California Residential Appliance Saturation Survey (RASS),[50] only about 37% of homes built before 1975 have central air conditioning (CAC). Slightly over 70% of the homes built between 1983 and 1992 have CAC. By 2001, 84% of new homes had CAC. Coincident with increased air-conditioning penetration, construction practice has moved towards slab-on-grade construction for virtually all California production homes built in the last 25 years. As a result, ductwork has become almost exclusively installed in the attic space where it is exposed to very hot and cold temperatures.

Duct insulation levels have increased over the past few years, but most pre-1991 homes have duct insulation levels of only R2.1[51] As shown in Figure 7 analysis using the ASHRAE 152[52] calculation methodology, increasing R2.1 duct insulation levels to R8 in a Fresno, CA home would generate similar seasonal duct efficiency improvements as reducing duct leakage from 40% to 20%. Losses are particularly high during peak day cooling events, when the temperature difference across the ducts can exceed 70 °F (with attic air at 130 °F and cool ducted air at 60 °F). Duct leakage compounds the duct heat loss to unconditioned space, by increasing the length of air conditioner run cycles due to the energy loss between the indoor unit and the supply registers. This effect is most pronounced during peak heat spells, when attic return leakage increases the load on the air conditioning system and the supply duct thermal losses are greatest.

[50] p. 23, Figure ES-23, 2009 California Residential Appliance Saturation Study, Executive Summary, CEC-200-2010-004-ES, KEMA, October 2010.

[51] Table R3-50 on page 3-81 of the 2008 Title 24 ACM has assumptions based on house vintage. http://www.energy.ca.gov/2008publications/CEC-400-2008-002/CEC-400-2008-002-CMF.PDF

[52] ANSI/ASHRAE Standard 152-2004, *Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems.*

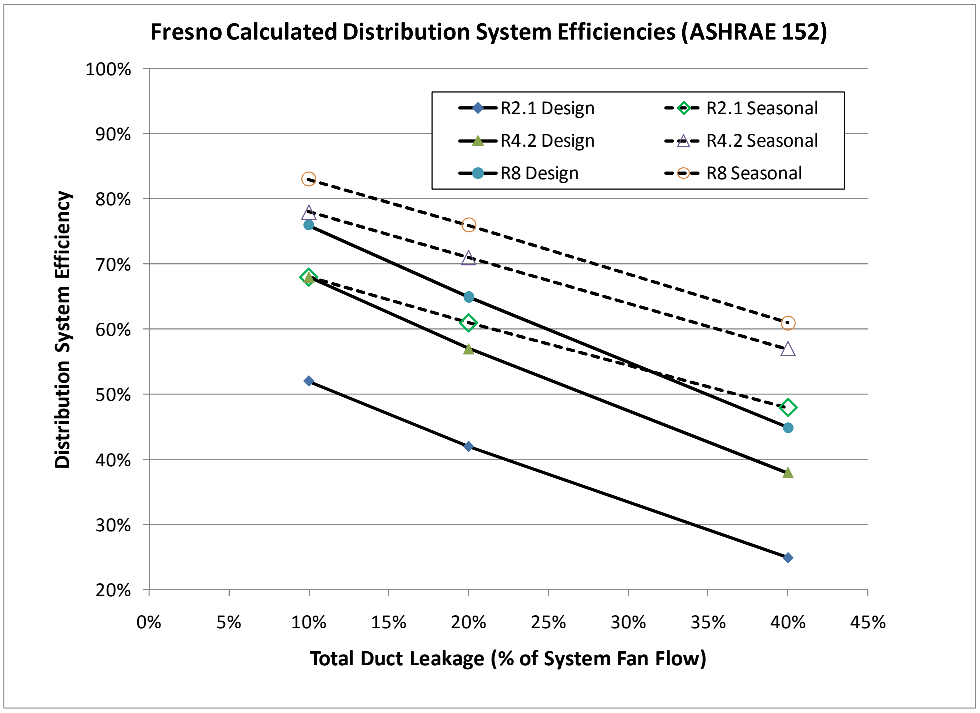

Figure 7. Duct Leakage Impacts on Distribution Efficiency

The combined impact of leaky and poorly insulated ducts can result in seasonal distribution efficiencies of 50% or less. Ideally, duct systems should be relocated to conditioned space or totally eliminated (ductless delivery systems), but realistically the best solutions involve duct leakage remediation and the addition of more duct insulation (and/or burying ducts under the blown-in attic insulation). Either manual sealing (with mastic, tape, and draw bands) or use of the aerosol duct sealing approach have been shown to reduce leakage by 50-80%[53] with aerosol techniques offering the advantage of sealing inaccessible leaks.

Duct leakage can occur on the system's supply side, return side, and at the air handling unit itself.[54] A duct test using a duct pressurization fan[55] is the standard approach to testing for duct leakage. By pressurizing the duct system to a standardized level (typically 25 Pascals or 0.1 Inches of Water Column, IWC), leakage can be normalized either to a "per square foot of living area" metric or as a percentage of system fan flow (the latter typical for California). The percent air leakage is calculated in comparison with an industry standard airflow rate of 400 cfm/ton, which is an unrealistically high number for most installations. Alternative duct leakage measurement techniques --such as pressurizing at one-half of measured duct system static pressure, using tracer gas, and the Delta Q method[56]--are potentially more accurate, but considerably more involved for any type of production program. Another method called the Zone

[53] See Jump 1996, Kallet 2000
[54] p. 2, Walker, I., Dickeroff, D., Delp, W. "Residential Forced Air System Cabinet Leakage and Blower Performance," LBNL 3383E, PIER Final Project Report, CEC-500-07-006, December 2008.
[55] The Energy Conservatory and Retrotec are two leading manufacturers of duct pressurization equipment and are found at: www.energyconservatory.com/products/products2.htm and http://www.retrotec.com/products/duct_testing_systems/q32_ductester/
[56] Sherman and Walker, 2002

DeltaP test has been proposed that addresses the artificially uniform pressure issue using inflatable bags inserted inside the duct system to test different parts of the system.[57]

In the 1990s, interest among DOE and HVAC industry experts led to the development of ASHRAE Standard Project committee 152P to develop a detailed duct efficiency calculation methodology. The resulting ASHRAE 152 Standard was developed at LBNL with input from numerous parties. The standard prescribes algorithms for the calculation of duct delivery efficiency based on duct surface area and location (e.g. attic, crawlspace), duct leakage and insulation levels, climate, and other factors. The methodology has been tested in the field[58] and was found to provide good agreement with field monitoring data.

Testing done at the Intertek Laboratory in Plano, Texas[59] (Figure 8) under the direction of Robert Mowris provides insight into the impacts on efficiency of duct leakage when ducts are located in attics.

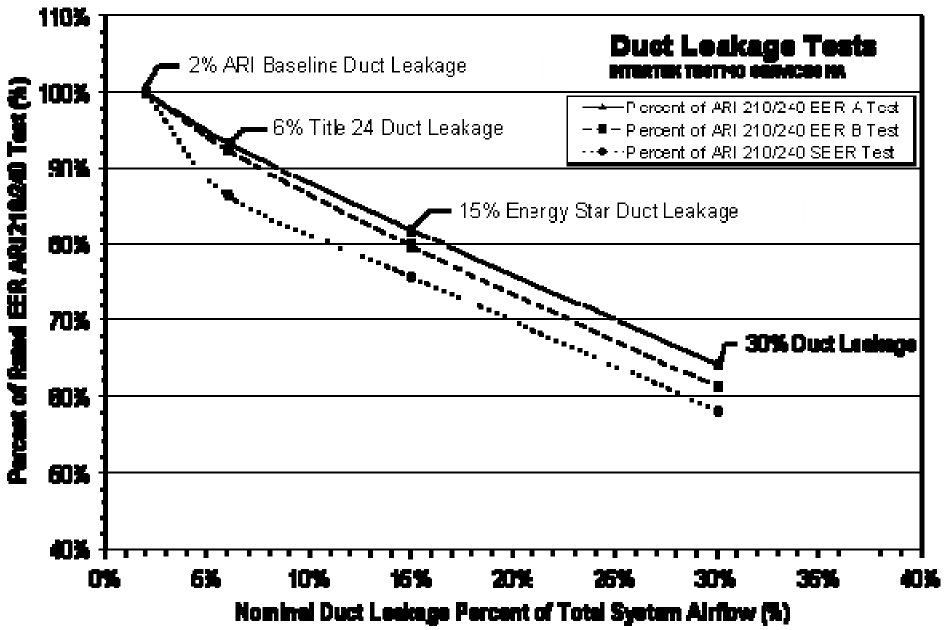

Figure 8. Percent of AHRI Tests v. Nominal Duct Leakage for Ducts Located in Attics[60]

The EER A test is at 95°F while the EER B test is at 82°F which shows how a hot attic impacts the EER. The attic is simulated with a chamber held at just under 120°F which is possible even

[57] p. 1, Moujaes, S., Nassif, N., Teeters, T. et. al, "Duct Leakage Measurements in Residential Buildings," Final Report NCEMBT-080215, University of Nevada Los Vegas, February 2008.
[58] Siegel, J., McWilliams, J., Walker, I. 2002. "Comparison Between Predicted Duct Effectiveness from Proposed ASHRAE Standard 152P and Measured Field Data for Residential Forced Air Cooling Systems."
[59] http://www.intertek.com/news/2009/11-09-hvac-facility/
[60] p. 8, Mowris, Robert, Verified Inc., Evaluation Measurement and Verification of Air Conditioner Quality Measures, Draft v. 4, as updated by additional testing in October 2010.

on mild weather days. It is also notable that duct leakage at an all too probable 30% has a much greater impact than a 40% undercharged system.[61]

5.1 Duct Testing Protocols and Sources of Error

Typical system operating pressures are up to five times higher in the supply plenum and up to five times more negative in the return plenum than at leakage test conditions (25 Pa). At the terminals, both supply and return, the pressures can be very low. Thus, the current test tends to overvalue leakage that occurs far from the air handler, and undervalue leakage at the air handler where operating pressures are greatest. This effectively directs remediation efforts equally throughout the distribution system[62], resulting in less emphasis at the furnace/plenum connections where the driving force is the greatest. Establishing a prescriptive requirement for technicians that they must first seal the connections and joints at furnace/air handler unit and the adjacent supply and return plenums could address this testing error. It is possible that an aggressive set of prescriptive requirements will eliminate the need for testing in those cases where the duct system is largely exposed but they must be accompanied by an effective quality control program.

According to Gary Nelson, founder of diagnostic equipment manufacturer The Energy Conservatory, duct leakage measurement repeatability can be affected by several factors, including the level of duct leakage, placement of the duct pressurization device and static pressure sensor, and the sealing technique at the registers[63]. In high leakage systems, the placement of the equipment and pressure sensor could result in deviations in leakage measurements of up to 15%[64], when the same measurement device is used in different locations. In relatively tight duct systems, common to homes and commercial systems that have

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[61] For complete information see : Draft Report – Evaluation Measurement and Verification of Air Conditioner Quality Maintenance Measures, prepared by VERIFIED, Incorporated, James J. Hirsch & Associates, and Intertek Testing Services (North America) under the auspices of the California Public Utilities Commission, April 2010. Robert Mowris summarizes the work as follows. Laboratory measurements of HVAC maintenance and installation measures were performed by Intertek Testing Services, an AHRI Certified laboratory, located in Plano, Texas. Testing was performed on a new split-system air conditioner with rated cooling capacity of 36,000 Btu/hour (3 tons) and matching condenser and evaporator coils with an AHRI rating of 13 SEER and 11.2 EER (per ARI 210/240). The air conditioner was tested with R22 refrigerant and five expansion devices including 1) original equipment manufacturer (OEM) piston metering valve (non-TXV), OEM pressure-equalizing thermostatic expansion valve (TXV), OEM hard shut-off TXV, non-OEM HSO TXV, and non-OEM electronic expansion valve (EXV). The forced air unit, evaporator, TXV, and ducts were located in a chamber maintained at conditioned space temperatures of 80F dry bulb and 67F wet bulb (per ARI 210/240) and 118F dry bulb and 78F wet bulb to simulate a hot attic. The following conditions were evaluated: 1) baseline 3-ton system per the ARI 210/240 test standard, 2) hot attic environment around components, 3) 25 and 50 feet line-set, 4) correct refrigerant charge, under charge of -5% to -40%, and over charge of +5% to +40% with a piston (non-TXV) and TXV metering devices, 5) evaporator airflow from 250 to 400 cfm per ton, 6) duct leakage of 2%, 6%, 15%, and 30%, 7) various TXV sensing bulb installation conditions including one strap, two straps, one insulation wrap with 50% overlap, and two insulation wraps with 50% overlap, 8) 30% to 80% condenser coil blockage, 9) 50% evaporator coil blockage, 10) combined or mixed measures, and 11) non-condensibles. Additional tests will be performed to measure the energy efficiency impacts of refrigerant restrictions and expanded superheat and temperature split target values. The Intertek test results indicate that HVAC maintenance and installation defects can significantly reduce air conditioning cooling capacity and energy efficiency.

[62] Register boots are a common area that is sealed with the standard duct pressurization test. Although important, other higher pressure parts of the system must be targeted.

[63] A smaller concern relates to calibration of the digital manometers used with the equipment. Mr. Nelson estimates that only 10% of the manometers in the field are returned for regular calibration. Although this is a low percentage, virtually all are found to be within spec, with less than half a percent of the manometers being out of spec by more than 5%.

[64] Personal communication with Gary Nelson, July 2010.

participated in DTS programs, the impact of device and sensor placement should result in reduced repeatability deviations on the order of 5%, or less.

A more critical technician impact relates to how the registers are physically sealed for testing. Typically, technicians place strips of masking or painter's tape over the grille face, and occasionally onto the drywall surrounding the grille. An alternate technique involves building up a "mask" ahead of time, and then securing the mask to the drywall, over the grille. This should result in a better seal when applied to the register, since placing tape while standing on a ladder complicates the goal of a perfect seal. Communications with Gary Nelson suggest that register sealing techniques could result in leakage variations of 3 – 7 cfm (at 25 Pascals) for each register sealed. This has been confirmed by a California HERS rater[65] who completes third-party duct pressurization tests required as part of HVAC equipment retrofits under Title 24. This rater consistently finds that his cfm leakage readings are 10-20% lower than the readings performed by the installing HVAC contractor, even when using the same digital manometer. Achieving higher repeatability levels will require specifications that explicitly document the register sealing and pressurization testing process. Field testing will be needed to develop specifications that are effective while not being overly cumbersome. It may be the case that a technology or technique will emerge that saves time, increases accuracy and gives repeatable results when applied by a number of technicians.

5.2 Duct Program Issues

Properly performed duct remediation--either through leakage reduction, added insulation, or both--will contribute to significant improvements in duct distribution system efficiency. ASHRAE 152 calculation results for a Fresno, CA home indicate that increasing cooling seasonal duct efficiencies from 50% to 80% are achievable. Field testing at 24 Sacramento homes found that adding R-6 duct insulation and reducing duct leakage from an average 35% to 18% increased delivery efficiency from 64% to 76%. This, in turn, resulted in estimated HVAC energy savings of 18%[66].

It is logical to require a leakage test before sealing the ducts, but in the context of a full-scale program, this approach may result in abuse. An incentive is paid for doing the pre-test that is generally not enough to cover the cost of doing the work. The incentive paid for doing the sealing is large enough that some contractors have been able to do the test and seal work for no charge to the customer. To make this work a high proportion of the sites must be sealed, which motivates technicians to determine that the leakage is over the program leakage threshold. If the program pays incentives for reducing leakage by a set percentage even more pressure is put on the technician to make the pre and post tests fit the criteria for incentive payments. More work is needed to develop a DTS program where pre-testing is reliable.

Alternatives that address this type of issue have been implemented in the Davis Energy Efficiency Program (DEEP)[67] and in the Puget Sound Energy[68] PSE program. In DEEP a sample

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[65] Personal communication with Allen Amaro, August 2010

[66] Jump, D., Walker, l., Modera, M. "Field Measurements of Efficiency and Duct Retrofit Effectiveness in Residential Forced Air Distribution Systems." ACEEE Summer Study Proceedings, 1996.

[67] Heschong Mahone Group; Evaluation, Measurement and Verification of the Davis Energy Efficiency Program, HMG Project #0307, September 22, 2004.

of houses in Davis, CA were tested by a test-only contractor and found to have leakage rates well above the program threshold. Based on this finding, the program only required testing of leakage after the sealing was done. Quality Assurance testing was done to verify that the post service leakage was below the level required by the program. In the PSE program, a prescribed set of actions is required that have been determined to achieve leakage reductions without testing. A research project is needed to further refine DTS program delivery. Testing of a statistically significant number of duct systems could establish when it is safe to assume that duct leakage is at a rate that does not require testing prior to sealing. Verification of the results of the PSE program would shed light on whether a prescriptive approach without testing works.

The energy savings benefits from reduced duct leakage are clear and well documented in the literature. Peak demand reduction is less well defined, however, as it depends on system sizing (cooling capacity vs. design load) and occupant thermostat control behavior. Coupling a DTS program with an air conditioner cycling program is one approach that can reduce peak demand and thus increase the program's value to the electric utility.

6 EER, Energy Savings, and Peak Demand Reduction

EER, or Energy Efficiency Ratio, is the standard metric used to quantify the efficiency of unitary air conditioning equipment at a specific operating condition. EER, expressed in units of Btu/Watt-hour, represents the combined steady-state sensible and latent cooling capacity divided by total unit power at a specified set of conditions[69]. Considerable effort has been undertaken in state-of-the-art testing laboratories to test systems under both "standard" and non-standard operating conditions, including cases that incorporate faults that contribute to lower observed field performance. Many experts[70] have questioned, however, whether EER can be accurately measured in the field given the difficulties in determining two key parameters that are used in the airside cooling capacity calculation: airflow across the evaporator coil and an average supply air condition (temperature and relative humidity).

EER can also be measured on the refrigerant side of the system. In laboratory testing both the airside and refrigerant side EERs are calculated and compared as a check on the validity of the test. They are expected not to be the same value but the difference should not be large. In the laboratory highly accurate "coriolis effect" meters measure the refrigerant mass flow. It is impractical to use them for field measurements. But, FDSI notes that:

> The method measures the change in enthalpy of the refrigerant multiplied by the mass flow rate to determine system capacity (Btuh). The enthalpies of the refrigerant are available from the refrigerant pressures and temperatures already being measured during standard service procedures. Mass flow rate and power can be derived from the

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[68] Bruce Manclark, Delta-T, Inc. and Bob Davis, Ecotope, "Report on Delta Q Field Testing", Puget Sound Energy, January 22, 2009. See also http://www.pse.com/solutions/foryourhome/pages/

[69] As per ANSI/AHRI Standard 210/240, nominal EER lab measurements are completed with 80 °F dry bulb / 67 °F wet bulb entering the evaporator coil; an airflow rate across the coil of 400 cfm/ton; and outdoor conditions of 95 °F dry bulb / 75 °F wet bulb.

[70] Personal communication with Hugh Henderson (August 2010) and Mike Lubliner (October 2010)

compressor performance data, or more practically from a normalized compressor map. The method has been used in the field with reasonable accuracy.[71]

The use of manufacturer compressor maps interjects an uncertainty which can be addressed given enough data to assess the probable distribution of compressor performance on either the high or low side of the mapped values. Collecting the field data to establish the relationship of compressor performance maps to "as found" compressor performance is another type of baseline that could be established with an adequate research effort.

The "Range of Lab Test Data" shown in Figure 9 is a collection of laboratory testing data that plots normalized EER (tested divided by nominal EER) on the Y-axis and number of tests on the X-axis. The figure highlights the wide variation in the EER that can be expected in the field, even without accounting for system efficiency degradation due to commonly found duct leakage of over 30% and duct thermal losses due to ducts with R2.1 insulation.

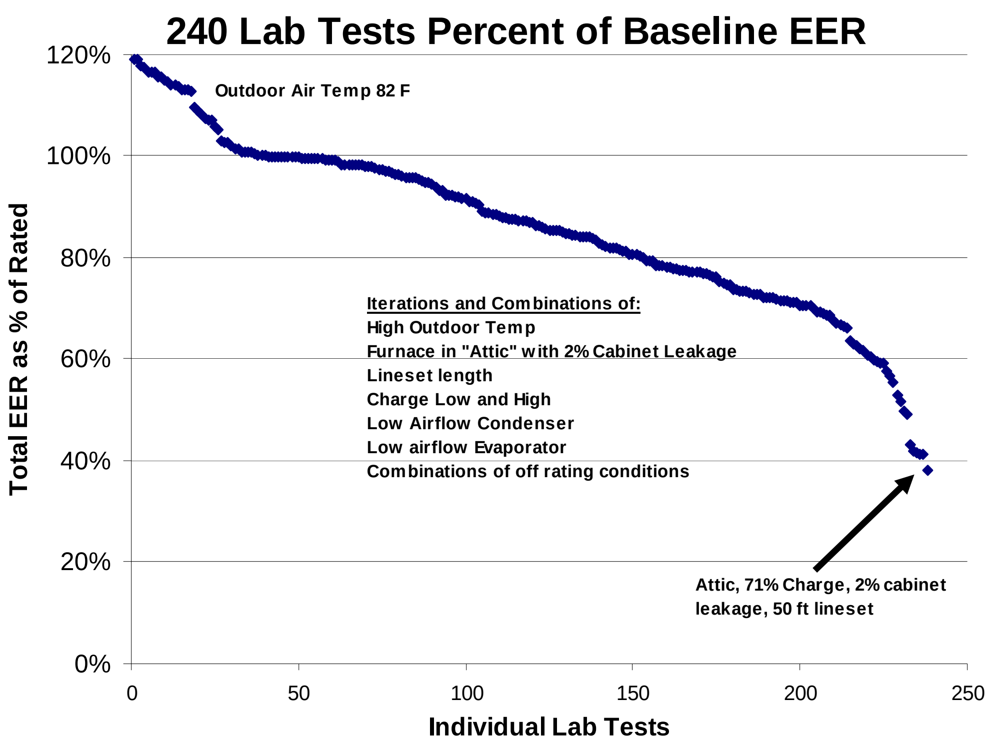

Figure 9. Range of EER Lab Test Data

Figure 9 EER results ≥100% are for properly installed systems running under more favorable than nominal operating conditions (e.g. higher supply airflow and/or lower outdoor temperatures). The "lower-than-baseline" results occur for systems operating at other than rated conditions and/or with combinations of introduced faults. The lowest EER ratios represent tests with the furnace in the "attic," furnace box leakage of 2%, 30% refrigerant undercharge, and a

[71] FDSI comments on the 112310 draft of the Study submitted to Brett Close, SCE.

refrigerant line set that is partially in the hot attic chamber.[72] All of the data shown are for tests without duct leakage, which would tend to drive the values even lower.

The discussion is further complicated by the fact that field impacts from energy efficiency measures are generally found to have smaller benefits than those observed in the lab[73]. This discrepancy can be attributed to many factors, including a lack of measurement accuracy, lack of calibrated instruments, program specifications that accept high levels of sensor inaccuracy, undiagnosed faults, an inadequate Quality Control verification program run by the VSP, programs that allow credit for small changes in charge, and human factors. It is critical for program designers to have a solid technical understanding of how uncertainties affect energy savings.

6.1 Evaluating Energy Savings

Reconciling expected energy savings versus observed savings in the field is critical for evaluating energy efficiency programs, but it is frequently problematic. Expected or deemed savings are based on lab testing, limited field testing, or engineering models, which have been shown to predict higher savings than observed in the field.[74] For field savings, the measurements presented in Section 7 of this report are used to determine one-time system efficiencies before and/or after the service measure. Unfortunately, the “measured” improvement in EER is unlikely to have the necessary statistical significance (for reasons discussed in Section 7), and, more importantly, it does not provide a solid basis for quantifying progress towards the ultimate goals: reduced annual energy consumption and peak demand.

Detailed monitoring of the units before and after improvements has historically been expensive, limited in scope, and difficult to interpret. Ideally the thermodynamic performance of the unit is measured along with its true RMS power consumption. A suite of sensors feeding into a data acquisition system that is downloading data to a server is required and will cost several thousand dollars. The raw data must be extensively analyzed to distill it to factors that can be used in hourly simulation models. Unitary HVAC equipment performance is usually modeled with a biquadratic function that is based on laboratory tested compressor performance.[75] Later in this Section, a method for deriving a modifying constant to the function from laboratory data is discussed. Implementing this procedure using field data was done in the KEMA report to estimate “degradation factors.”[76] But the KEMA report was clear that results did not achieve the level of 10% precision at a 90% confidence level because: “Overall, the wide variance of savings observed in the sample suggests that actual savings in the population varies much more than anticipated and that much larger sample sizes would be necessary to achieve a high level of confidence in the calculated average savings per ton.”[77] It also appears to be the case that the few units that did generate pre and post EERs did not have the contractor service verified as being up to the RCA program standards so that it is not known what was actually done.

[72] Testing completed by Robert Mowris at Intertek March 2010, personal communication. http://www.verified-rca.com/
[73] KEMA 2010 and ADM 2008
[74] p. 11, KEMA, February 2010.
[75] p. 36, KEMA, February 2010.
[76] p. 10, KEMA, February 2010.
[77] p. 118, KEMA, February 2010.

The wide variation is due to technical, mechanical, climatic and behavior diversity. The normal procedure is to use hourly[78] building energy simulations to predict the impact of changes in EER. Determining the savings requires simulations that model differences in system efficiency based on variations in operating conditions. Ideally it also requires behavioral models that reflect the highly variable occupant thermostat control patterns[79] and the impact of the "take back" effect where occupants use the air conditioner more after it has been made efficient. Monte Carlo techniques or other approaches would be useful in understanding the interactive effects of behavior (e.g., thermostat control patterns), hourly load, system sizing, and HVAC system improvements. All these "unknowns" essentially support the strategy of widespread pre- and post-energy monitoring over a large customer sample. Such an approach, combined with indoor temperature and thermostat control behavior monitoring, could provide data that would be useful in validating models. At present there is not enough data and analysis to clearly define issues and determine effective approaches to resolving these issues.

6.2 The DEER Database

The Database for Energy Efficient Resources (DEER) is a CPUC-sponsored database designed to provide well-documented estimates of energy and peak demand savings values, measure costs, and effective useful life all with one data source. DEER[80] was originally developed in the 1990s. It has undergone updates and revisions as new information about measures becomes available and better data for refining the estimates are received. Current DEER RCA and DTS assumptions are based on available research including EM&V studies that the consultant team deems valid. There is no obvious and organized peer review of the deliberations and decisions made by the DEER team which makes DEER not transparent to stakeholders who must use it or explain why they are not using its results. There is an ongoing debate about the technical revision process that does not necessarily use the most up-to-date information. For example, it is reported that the DEER DTS assumes that half of the total leakage is to the outside which is in contrast to the 80 to 90% values found for California houses[81,82].

DEER was designed for use in mass market program design and implementation and was not designed for model-specific technologies and specific operating conditions. For example:

- DEER uses heating and cooling thermostat schedules as the lever to "calibrate" the simulation results to the energy use results of the Residential Appliance Saturation Survey (RASS) load data. The current strategy uses multiple assumed thermostat schedules and weighting factors to bring space conditioning energy use in line with targeted RASS climate zone values.
- RASS presents problems of its own since it is a conditional demand analysis that fits a function to available data from a sample of dwellings thought to be representative of a

[78] Shorter time step models may be better suited to capture system cycling effects.
[79] Peterson, G. and Proctor, J. 1998. "Effects of Occupant Control, System Parameters, and Program Measures on Residential Air Conditioner Peak Demands", Proceedings of 1998 ACEEE Summer Study on Energy Efficiency in Buildings
[80] The DEER database results rely heavily on the DOE2.2 simulation tool.
[81] Personal communication with Mark Modera (July 2010)
[82] Davis Energy Group, "Residential Construction Quality Assessment Report- Phase II Final Report", California Energy Commission, 400-98-004.

type and vintage of building in a Climate Zone. This approach cannot tell the difference between an efficient air conditioner, an inefficient one running only on peak, or a fault-ridden unit that can only operate under moderate weather conditions.

- DEER provides <u>average</u> usage and <u>average</u> savings. It does not provide information on the full spectrum of installed air conditioners, which include very efficient systems and very inefficient ones, nor how the occupants use them. If energy and demand savings are the true objective of effective programs, marketing of HVAC services should be inherently targeted towards those who value/need air conditioning and heating based on their usage.
- DEER applies a high-level view of the coincident demand that does not allow assessment of peak impacts at the building level, local distribution transformer, and local substation levels.

The following example looks at current savings assumptions for an existing house in CEC Climate Zone 10 (Riverside County). Figure 10 plots DEER projected savings for RCA and duct leakage remediation improvements. Interestingly, the impact of duct leakage remediation is small relative to the RCA impacts. On average, the 12% leakage reduction translates to only about a 5 percentage point increase in savings (16.7 – 11.6 in Figure 10)[83]. One factor affecting the DEER savings impact is the assumption that only 50% of the duct leakage occurs to the outdoors. In reality, leakage to outside space is closer to 85% in typical California homes with attic ducts. The symmetry in performance degradation around proper charge is not in keeping with laboratory data, and there is no distinction between fixed orifice and TXV systems even though the impacts are significantly different. As is the case in all of the DEER values there is not a clear indication of the uncertainty that surrounds them based on the reference documents, simulation uncertainty when using DOE2.2, and the approximations inherent in the use of building vintages.

[83] Numerous studies identified in Section 5 have found much higher savings associated with duct leakage remediation. A large scale proprietary duct leakage study of over 1000 high use customers in the Southeastern U.S. found whole house annual electrical energy savings exceeding 17%. Personal communication with Danny Parker (August 2010)

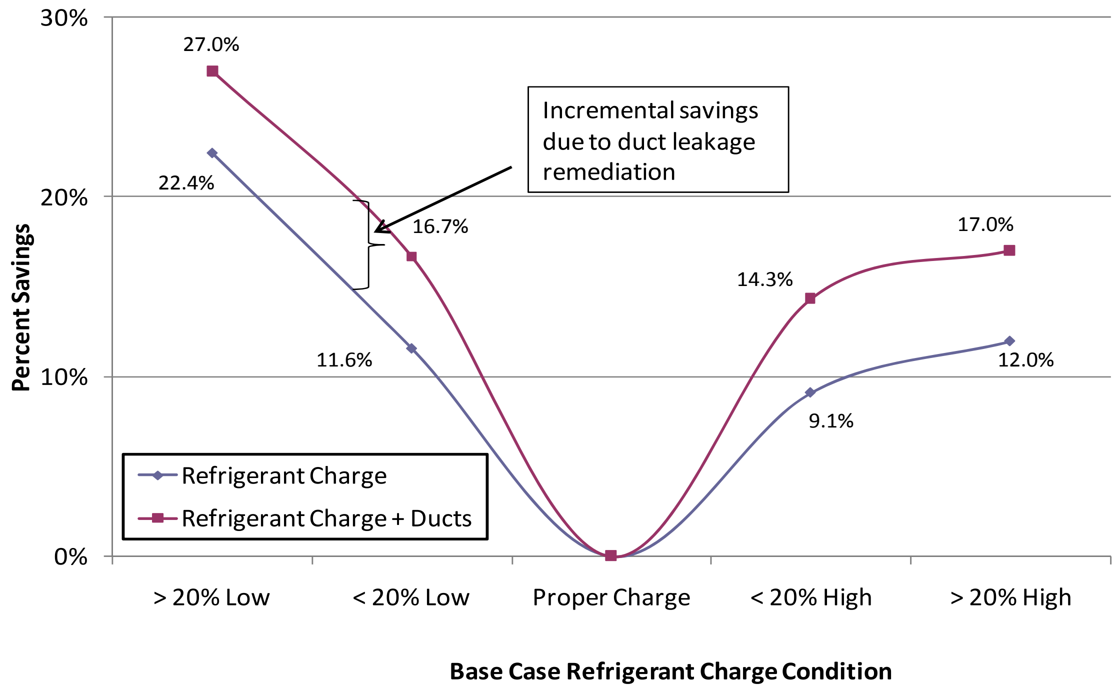

Figure 10. DEER Projected Annual Savings for a Climate Zone 10 Home

The use of accurate simulation models is critical for characterizing the benefits associated with individual and combined multiple faults, as well as defining how future programs should be structured. A key aspect of fully understanding laboratory test data fault interrelationships involves proper normalization of the data. Air conditioners are rated under steady-state conditions at a single condition, but actually operate under a wide range of conditions, airflow rates, and varying cycle durations (non-steady-state). The performance of an air conditioner generally varies primary on the following operating parameters: Outdoor (or condenser entering) dry bulb temperature (TAO); evaporator entering dry bulb (EDB) and wet bulb (EWB) temperature; evaporator airflow rate (CFM); and total unit power (WATTS).

For any air conditioner, a performance map (or set of empirical/theoretical curves) can be developed to represent total cooling capacity (QT), sensible cooling capacity (QS), and efficiency (EER). The performance maps which predict performance (the dependent variables) as function of operating conditions (the independent variables) are of the form:

$$QT = F_1(\text{ TAO,, EWB, CFM })$$
$$QS = F_2(\text{ TAO, EDB, EWB, CFM })$$
$$EER = F_3(\text{ TAO, EWB, CFM})$$

Other dependent variables can be used instead, such as latent capacity (QL), sensible heat ratio (SHR), and compressor power input (WATTS). If any three (3) of these dependent variables are known, then the others can be determined (using the definitions: SHR=QS/QT, QT = QS + QL, EER = QT/WATTS). To determine the portion of capacity that is sensible and latent (QS, QL or SHR), the independent variable EDB is also required. To find total capacity or efficiency (QT, EER or WATTS) then only the wet bulb (EWB) is required (until coil dry out occurs or QL=0, then EDB is required).

When faults related to improper refrigerant charge are added, the performance maps become much more complicated. The modified functions consider the impact of charge (i.e., f_r = fraction of nominal charge):

$$QT = F_{1a}(TAO, EWB, CFM, f_r)$$
$$QS = F_{2a}(TAO, EDB, EWB, CFM, f_r)$$
$$EER = F_{3a}(TAO, EWB, CFM, f_r)$$

This more complicated function requires that considerably more laboratory data be collected to fully account for the impact of improper charge (i.e., "the fault") at both nominal and off-design conditions. If the impact of the fault can be shown to be independent of other operating conditions, then the needs for data collection from the laboratory can be significantly reduced. So the first test of any data analysis process should be to determine if this simplification is justified. Stated mathematically:

$$QT = F_1(TAO, EWB, CFM) \mathbf{x} \; F_{1b}(f_r)$$
$$QS = F_2(TAO, EDB, EWB, CFM) \mathbf{x} \; F_{2b}(f_r)$$
$$EER = F_3(TAO, EWB, CFM) \mathbf{x} \; F_{3b}(f_r)$$

6.3 An Example of Useful Data Normalization

In 2001, PG&E[84] laboratory testing on an R22-charged unit produced results that showed performance variations as a function of refrigerant charge, expansion device type, and operating conditions. Figure 11 presents the PG&E data normalized by the nominal EER (95 °F outdoors, and 80 °F dry bulb and 67 °F wet bulb entering the coil). This presentation of the data assumes that the impact of refrigerant charge fraction has a unique impact at each different operating condition. As shown in the figure, the ratio of the test EER divided by the rated EER drops from almost 1.2 at 82 °F outdoor conditions to below 0.8 at 115 °F. Also, the "Orifice" or fixed orifice data shows that at 80% of the factory charge performance at 115 °F is about 70% of rated EER.

To test this assumption we can also normalize the data by separating performance variations due to operating conditions from performance variations due to refrigerant charge. Stated mathematically, we test the assumption that:

$$F_{3b}(f_r)= F_{3a}(TAO, EWB, CFM, f_r) \; / \; F_{3a}(TAO, EWB, CFM, 1)$$

The data from Figure 11 are normalized by dividing the efficiency at each point by efficiency corresponding to the measured performance with nominal charge for each outdoor temperature condition.[85] Figure 12 shows that the curves essentially collapse to a single trend. The large "+"

[84] p. 22, Davis, R., "Influence of the Expansion Device on the Performance of a Residential Split-System Air Conditioner," Report No. 491-01.4, PG&E, Technical Application Services, January 2001.
[85] Analysis from Appendix D of Sachs, H. , Henderson, H., Shirey, D., De Forest, W., "A Robust Feature Set for Residential Air Conditioners, ACEEE Report Number A081" 2009.

symbols represent the average fraction at each charge point for all the operating conditions. Plotting the uncertainty of the lab data would show overlap of the different operating conditions lines thus supporting the use of the "+" average. A similar analysis for "wet" conditions (80 °F/ 67 °F) shows similar results, indicating that the differences between the wet and dry conditions appear to be minor. Therefore, the impact of charge is essentially independent of operating conditions. Only the type of expansion device is important. Also the impact of undercharge is not significant until it is at 80%. Overcharge impacts are much less significant even though they are more likely to damage equipment. The incorrect charge tolerance of TXV systems is apparent and is the subject of additional research.

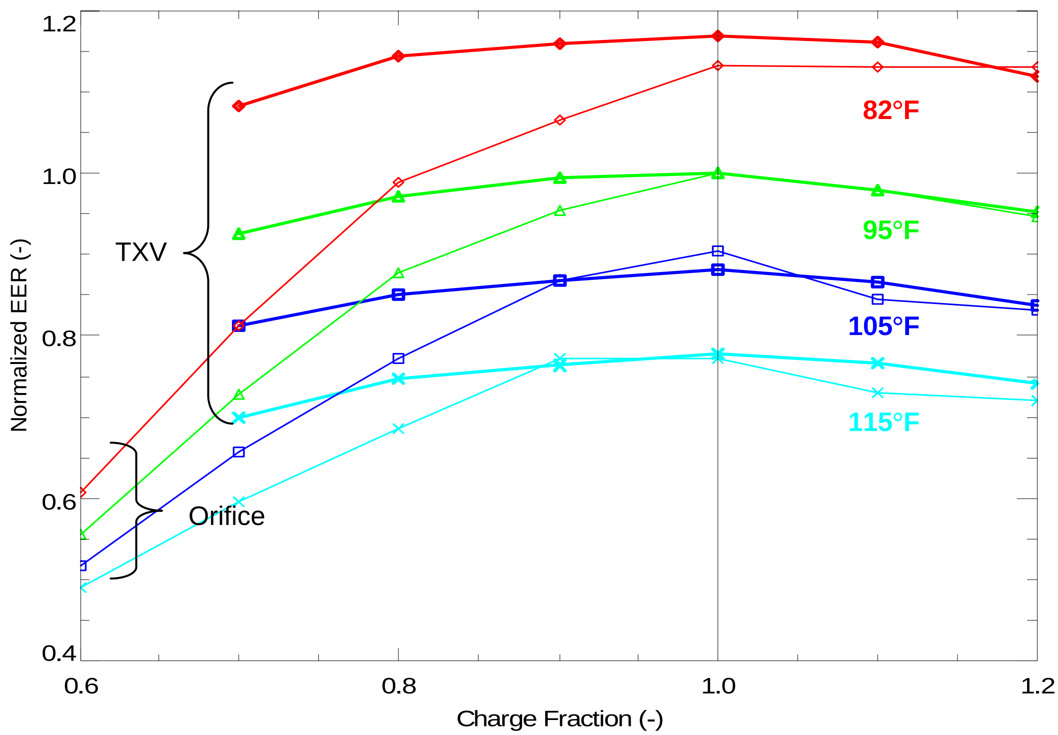

Figure 11. Normalized Efficiency Plot

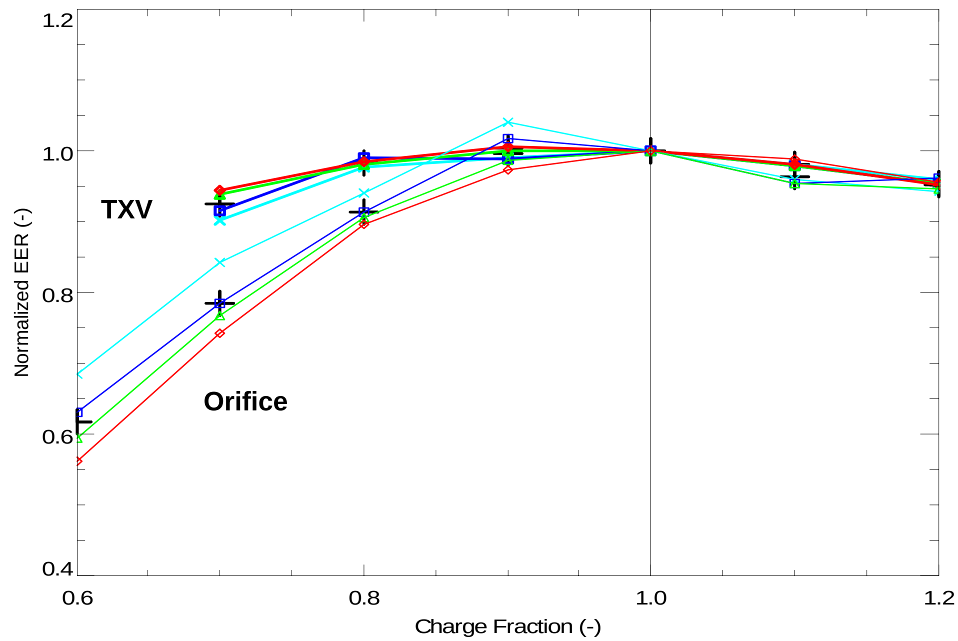

Figure 12. Normalized Efficiency Impact Charge at Dry Conditions (80 ºF /63 ºF entering)

6.4 The Lesson of Data Normalization

The lesson from this exercise is that any laboratory data collection effort should be aimed at first collecting sufficient data to prove (or disprove) the validity of simplifying the results via data normalization. The goal is always to test the simplifying assumption that the impact of the fault is independent of the operating conditions. This allows the impact for fault A – or $F_A(f_A)$ – to be "superimposed" on the performance map for the normally functioning unit and a more generalized and useful result to predict program-wide savings. The next step in the analysis is to test whether the impact of multiple faults are independent and can be independently superimposed.

If the laboratory test data can be used to show that the impact of faults are independent of operating conditions, then the resulting simplifications are warranted, and they can be easily implemented into program documents, analysis procedures, and simulation totals to provide a clear and transparent indication of impacts and savings.

7 Uncertainties in Site Measurements

In-field measurements performed accurately, with calibrated instrumentation, and a robust diagnostic protocol are essential for evaluation of system performance and status. No measurements are free of errors, and while it is critically important to maintain calibrated equipment, even in the best of circumstances, with the best equipment, the determination of system performance will still have uncertainty. It may not be typical for HVAC technicians to calibrate instrumentation routinely and it is almost never done using National Institute of Standards and Testing (NIST) traceable equipment. Without a stakeholder process to consider all aspects of the issue it is not known whether or not NIST traceability is necessary and in any case what are the protocols for calibration. To the technician in the field, the primary goal is to provide comfort to the customer[86], not to optimize the unit's energy efficiency. Maintenance and repair of HVAC systems is dependent upon the experience and knowledge of senior technicians who can effectively solve problems. Instrumentation and measurements support the diagnosis but are not determining factors for the successful completion of the work. Achieving energy efficiency puts a new burden on the work done by the average HVAC technician. The technician must learn to rely more heavily on the measurements. In order to increase accuracy and reduce the uncertainty in the measurement, a combination of methods must be utilized.

7.1 Instrument accuracy

Instrumentation is the first root of uncertainty of measurement. When an instrument is used to measure a physical property, the instrument's accuracy must be taken into account in the reported reading. Commonly used instruments can vary in their levels of accuracy. Higher accuracy units are not in wide use because they cost more, are often more fragile, and must be sent off to be calibrated. Calibration errors add a second layer of uncertainty in measurement, which can only be addressed by implementing a consistent and regular calibration protocol. The third layer of uncertainty relates to how the measurement is conducted. In this review it is noted that some significant attributes of uncertainty were related to the conduct of the measurement itself, and standards need to be developed in the methods of measuring unitary HVAC equipment performance. For example, calculation of superheat on a split system, with refrigerant lines run in an attic and/or exposed to ambient conditions, using the surface temperature of the suction line near the service port where the pressure is taken will be higher than the actual superheat calculated using the surface temperature of the suction line as it leaves the evaporator coil[87]. The fourth layer of uncertainty occurs when measurements on a system are taken at different times and with different instruments. Measurements taken by the HVAC technician and EM&V technician are conducted under different ambient and attic conditions, and the effect on the measurements will be highly uncertain diminishing the value of comparisons.

Measurement of refrigerant line temperature (later used in superheat and subcooling determination) is performed by connecting a temperature measurement device to the bare and clean copper line, with insulation and thermal grease. Haorong Li's Dissertation[88] summarized the evaluation of the difference in measuring line temperature with a resistance thermal device (RTD) versus a thermocouple. The factors affecting measurement include the presence of insulation, mechanics of heat transfer, and the temperature differential of line and ambient. Li summarized the heat transfer to an RTD in an equivalence resistance model, and concluded that even under the best of installations; the error in measurement is 20% of the total differential temperature, or 20 °F if there is a 100 °F differential temperature. A thermocouple in the same condition is capable of an error of 1.6%, or 1.6 °F if there is a 100 °F differential temperature. This illustrates the need to consider not only the published accuracy but also the accuracy that is dependent on the application. During the demonstrations by the VSPs at the Technical Forum another important observation was that suction line surface temperature is higher on the tube bottom due to the returning compressor oil, indicating that the probe must be located on the top of the tube. Technicians are taught to measure at the 3 or 9 o'clock positions to avoid this

[86] Given service call scheduling constraints, this often comes down to is it blowing cool air?
[87] If the attic is hot, but certainly less so if the test is completed on a cool day or in the morning.
[88] p. 267-270, Li, Haorong, "A Decoupling-Based Unified Fault Detection and Diagnosis Approach for Packaged Air Conditioners," PhD Thesis, Purdue University, August 2004.

problem but protocols are needed to make it a standard practice. Also at the Technical Forum, results from an exploratory test done by Robert Davis at the PG&E laboratory in San Ramon was presented showing the impact of using different sensors mounted in different manners on the accuracy of pipe surface temperature measurements[89]. The best sensor and mounting method was the insulated and calibrated bead thermocouple measured 39.3 °F which represents a 3% error.[90] This contrasts with a measured 7% error when using a clamp-on thermocouple as commonly used and as allowed by the 2004 RCA specifications[91].

Proctor Engineering Group has conducted additional testing on 5 commonly used temperature probes in support of Title 24 revisions. Figure 13[92] plots the results of the testing. Of particular concern is the time it takes for the relatively high mass Thermistor probe to reach the terminal temperature.

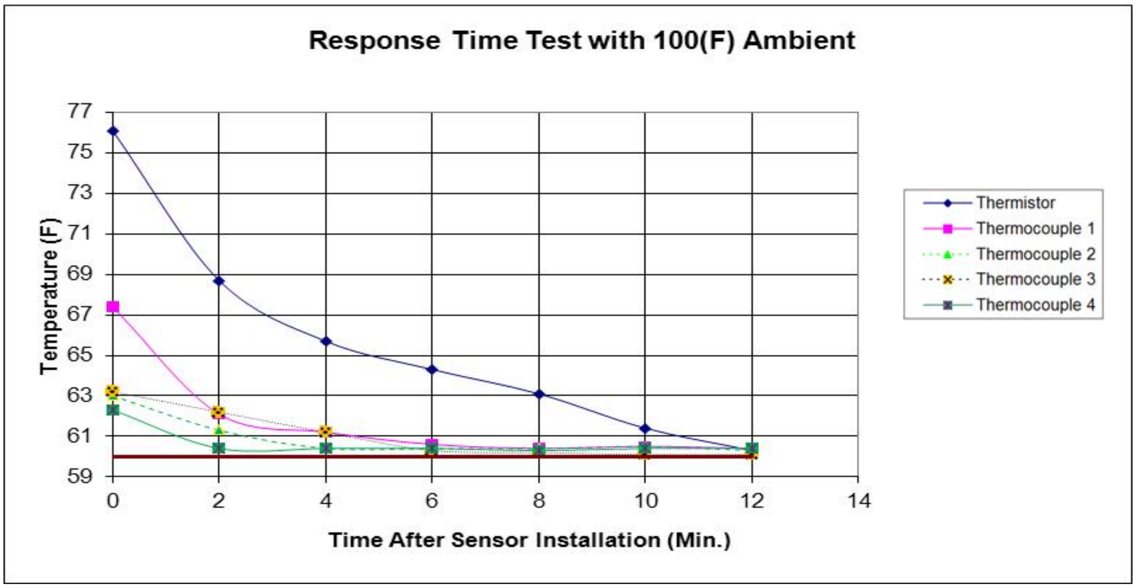

Figure 13. Response Time of Temperature Probes

This research also found that one clamp-on thermocouple of the type preferred by technicians worked very well while in general thermistors performed poorly. The work of Li, Davis and Proctor supports the assertion that just considering the published accuracy of sensors is not sufficient. Additional testing is needed to develop the measurement and instrument specifications to support technician service work. Robert Mowris has pointed to the development of shower head test standards as being a possible template for the process needed to establish instrumentation standards.

System characteristics or variables are metrics of system performance that cannot be measured directly. They are obtained from a system equation that involves direct measurements of lower-

[89] The suction line surrogate in this test was a 5/8" diameter pipe with 37.6 °F water circulating through the pipe in a room held at 94.3 °F (resulting temperature difference of 56.7°F).

[90] Calculation: 94.3 room temperature – 37.6 water in pipe temperature = 56.7; 39.3 bead temperature measurement – 37.6 water temp = 1.7; 1.7/56.7 = 0.03 for a 3% error.

[91] p. 13, Davis, R., Experimental Analysis of Tube Surface Temperature Measurements, Laboratory Test Report # 491-07.6, Applied Technology Services, PG&E, San Ramon, December 6, 2007.

[92] Hairrell, Adrian "Laboratory Report on Refrigerant Line Temperature Probes" 2010, Proctor Engineering Group. Text box inserted to remove brand and model designations of tested sensors.

level variables, or measured variables. Uncertainties[93] in the measured variables are published in instrument documentation, or can be obtained by testing the instrument. Assuming the uncertainties of the measured variables are not correlated, the total uncertainty in the system variable can be approximated using the delta method that is:

$$U_R = \sqrt{\sum \left(\frac{\partial R}{\partial x_i} u_{x_i} \right)^2}$$

Where:

$\frac{\partial R}{\partial x_i}$ is the sensitivity coefficient (partial derivative of Performance Metric with respect to measured variable)[94]

u_{x_i} is the uncertainty of the measured variable

Determining the combined effect of instrument measurements on the uncertainty in a system characteristic involves first defining the equation of the characteristic. For example, superheat is a system characteristic that is determined by taking the difference in suction line temperature and the saturated refrigerant temperature at the measured line pressure. We define four system characteristics, calculated from observable measurements, to be:

$$T_{superheat} = T_{suction\ line\ surface} - T_{saturation\ (Psuction)}$$

$$T_{subcool} = T_{saturation\ (Pdischarge)} - T_{liquid\ line\ surface}$$

$$EER_{total} = \frac{\text{air flow rate(ft3/hr) * air density (lbs/ft3) * change in enthalpy (Btu/lb)}}{\text{compressor watts + condenser fan watts + blower watts}}$$

$$EER_{sensible} = \frac{\text{air flow rate(ft3/hr) * heat capacity of air (Btu/ft3,°F) *(returnair-supplyair temp) (°F)}}{\text{compressor watts + condenser fan watts + blower watts}}$$

The total uncertainty in the system variable is related to the sensitivity coefficients, the calculated partial derivatives of the system variable with respect to the measured variables. Subcooling temperature is dependent on two measurements, liquid line surface temperature and discharge pressure. The uncertainty in subcooling is determined from the partial derivatives with respect to these measurements and the stated accuracies of both devices.

For ease of calculation, we input these system equations into an equation solver with built-in psychrometric and refrigerant charts called EES (Engineering Equation Solver)[95]. The sensitivity coefficients rely on in-field or laboratory measurements and the unit systems[96] used.

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[93] As used in this analysis "uncertainty" is defined as half the width of a confidence interval or a standard deviation around a measurement value.
[94] The partial derivatives depend on the values of the lower level variables and so (typically) unlike the uncertainties of the lower level measurements, it will depend on the value of "x." The resulting sensitivity coefficient can change over the range that can be encountered. This can result in situations in which one of the measured variables is the critical one within part of the operating range, but another becomes more critical in another range.
[95] http://www.fchart.com/
[96] Inch-pound

Two sample measurements of a three-ton R410-A split system (with TXV) are examined below to observe the impact on the sensitivity coefficients. Both conditions examined are extracted from data reported by Herrick Laboratories in the ASHRAE Report 1173-RP, tables A3 and A4 respectively. In the ASHRAE report, the tables[97] detail the units being tested and the specifics of each test. The data for the tests can be found in the ASHRAE report appendices. Test A3.1 is on page 245. This test varies indoor humidity from 19 to 72% RH which is a range of dewpoint temperatures of 32.57 °F to 69.57 °F. All other conditions are kept constant at the base case levels of AHRI Standard 210/240. Test A4.4 is on page 248 and varies evaporator airflow from 1201 to 620 with the "4" having airflow of 912 or 304 cfm/ton.

Measurements	Units	ASHRAE Report Series A3.1	ASHRAE Report Series A4.4
Suction Line Temperature	F	49.09	43.08
Suction Pressure	psig	134.73	119.27
Liquid Line Temperature	F	102.53	99.75
Discharge Pressure	psig	404.63	395.53
Return Air Dry Bulb	F	78.42	76.41
Return Air Dew point	F	32.57	33.31
Supply Air Dry Bulb	F	53.57	48.23
Supply Air Dew point	F	32.92	33.4
Flow Rate	CFM	1211	912
Atmospheric Pressure	kPa	100.5	100.5
AHU Power	W	450	360
Compressor Power	W	2860	2720
Condenser Fan Power	W	150	150

Table 2. Data for Sensitivity Coefficient Calculations

Table 2 data is the source for calculating the sensitivity coefficients for the two tests (A3.1 and A4.4) on the same system operating under different conditions. Table 3 shows the results. The "% Difference" column shows how the sensitivity coefficients relate to each other.

[97] P. 91, ASHRAE 1173

Calculation	Measured Variable	Units	Sensitivity (∂Sh/∂Measurement) ASHRAE Report Series A3.1	ASHRAE Report Series A4.4	% Difference
Superheat					
	Suction Line Temperature	F	1	1	0.0%
	Suction Pressure	psig	0.4368	0.479	9.2%
Subcooling					
	Liquid Line Temperature	F	1	1	0.0%
	Discharge Pressure	psig	0.1891	0.1924	1.7%
EER					
	Return Air Dry Bulb	F	0.3527	0.2836	21.7%
	Return Air Dewpoint	F	0.2645	0.217	19.7%
	Supply Air Dry Bulb	F	0.3695	0.2992	21.0%
	Supply Air Dewpoint	F	0.2645	0.2174	19.5%
	Flow Rate	CFM	0.000125	0.0001537	20.6%
	Atmospheric Pressure	kPa	0.09129	0.08382	8.5%
	AHU Power	W	0.002627	0.002604	0.9%
	Compressor Power	W	0.002627	0.002604	0.9%
	Condenser Fan Power	W	0.002627	0.002604	0.9%
Sensible EER					
	Supply Air Dry Bulb	F	0.4024	0.3257	21.1%
	Return Air Dry Bulb	F	0.4024	0.3257	21.1%
	Flow Rate	CFM	0.008258	0.01006	19.7%
	AHU Power	W	0.003021	0.00298	1.4%
	Compressor Power	W	0.003021	0.00298	1.4%

Table 3. Calculated Sensitivity Coefficients

Using Table 3 data the impact of changes of the sensitivity coefficients on uncertainty of the system variables is calculated in Table 4.

	ASHRAE Report Series A3.1			ASHRAE Report Series A4. 4		
Calculation	Values Reference	Uncertainty of Value	Uncertainty as % of Reference Value	Values Reference	Uncertainty of Value	Uncertainty as % of Reference Values
Superheat	8.18	± 1.01	12.3%	13.33	± 1.03	7.7%
Subcooling	12.29	± 1.10	9.0%	9.23	± 1.11	12.0%
EER	8.88	± 0.93	10.5%	8.28	± 0.75	9.1%
Sensible EER	8.88 (SHR 1)[98]	± 1.03	11.5%	8.28 (SHR 1)	± 0.83	10.0%

Table 4. Impact of Test Conditions on Uncertainty

Table 4 displays both the uncertainties as a percent of reference values and how they change based on the test conditions. In the field, conditions are constantly changing, so that at best an "equivalent" or "adequate" steady state condition is reached after 15 minutes. Between tests conducted on different days the changes can be dramatic. To get an appreciation of the impacts, the simplified situation presented by the laboratory test data is instructive. The uncertainty varies from a low of 7.7% for A4.4 superheat to a high of 12.3% for A3.1 superheat even under these tightly controlled laboratory conditions.

In summary, Table 2 presents the test conditions from which that the uncertainty is calculated. Table 3 presents the partial derivates as defined in delta method equation. Table 4 shows how the uncertainty will change based on the test conditions, which affect the partial derivative calculations. In essence, the uncertainty in a calculated variable is determined not only by the uncertainty in the measurements taken, but the measurements themselves (the reference conditions). Table 4 gives a demonstration of how much that can change by comparing two test conditions.

A review of published instrument accuracies and total uncertainties in system variables from several laboratory-testing facilities, Verified Service Providers (VSP), the AEC 2004 standard, and the Technical Forum-recommended revision to the AEC standard are compared in Table 5. The "Current Contractor" values are derived from the AEC report for PG&E.[99] As has often been the case, these values are controversial and subject to challenge especially when field test instrumentation is close to or better than lab instrumentation. Several VSPs take issue with the claims made by EM&V providers. Settling this issue, and other controversies, will take the work of an independent lab performing side by side comparison testing. The purpose of the table is to

[98] While other ASHRAE 1173 laboratory tests have sensible heat ratios (SHR = Sensible Capacity / Total Capacity) that are not 1.0 these particular tests do and thus EER Total is the same as EER Sensible. This is desirable in the hot dry west where latent cooling is minimized in the design process.

[99] Architectural Energy Corporation (AEC), Commercial HVAC Refrigerant Charge & Airflow and Economizer Verification Study, Contract #4600016485, Job I.D. #06 CEE-T-3589, Task 3: Conduct Additional Research, Draft, December 15, 2006.

provide data for discussing the importance of instrumentation uncertainty and to show the range of uncertainties.

Uncertainty										
		Lab		EM&V		AEC 2004	VSP		Contractor	Revised AEC
Measured Variables	Units	Min	Max	Min	Max		Min	Max	Current	2010 Tech
Supply Air (Dry Bulb)	F	± 0.05	± 2.3	± 0.18	± 0.50	± 1.5	± 0.7	± 1.5	± 2.1	± 1.5
Return Air (Dry Bulb)	F	± 0.05	± 1.8	± 0.18	± 0.80	± 1.5	± 0.7	± 1.5	± 2.1	± 1.5
Outside Air (Dry Bulb)	F	± 0.05	± 1.8	± 0.18	± 1.00	± 1.5	± 0.7	± 1.5	± 2.1	± 1.5
Supply Air (Wet Bulb)	F	± 0.05	± 1.8			± 1.5			± 2.1	
Return Air (Wet Bulb)	F	± 0.05	± 1.8			± 1.5			± 2.1	
Outside Air (Wet Bulb)	F	± 0.05	± 1.8			± 1.5			± 2.1	
Supply Air (RH) (DEWPOINT)	% | F	± 0.005	± 0.4	± 1 %	± 2 %	± 3 %	± 2.0 %	± 3 %	± 3 %	± 2 %
Return Air (RH) (DEWPOINT)	% | F	± 0.005	± 0.4	± 1 %	± 2 %	± 3 %	± 2.0 %	± 3 %	± 3 %	± 2 %
Outside Air (RH) (DEWPOINT)	% | F	± 0.005	± 0.4	± 1 %	± 2 %	± 3 %			± 3 %	
Condenser Discharge (Dry Bulb)	F	± 0.05	± 0.9	± 0.2	± 1.0					
Suction Line (Dry Bulb)	F	± 0.30	± 0.9	± 0.5	± 1.5	± 1.5	± 1.5	± 3.2	± 3.5	± 1.5
Liquid Line (Dry Bulb)	F	± 0.30	± 0.9	± 1.0	± 1.5	± 1.5	± 1.5	± 3.2	± 3.5	± 1.5
Suction Pressure	psig	± 0.3	± 1.1	± 0.13	± 1.35	± 4.04	± 1.35	± 4.04	± 4.04	± 1.00
Discharge Pressure	psig	± 1.0	± 3.2	± 0.40	± 4.05	± 12.14	± 4.05	± 12.14	± 12.14	± 1.00
Condenser Power (True RMS)	W	± 0.2	± 10.0	± 1.5	± 3.0	± 3.0				± 3.0
Compressor Power (True RMS)	W	± 2.9	± 14.3	± 28.6	± 57.2	± 57.2				± 57.2
AHU Power (True RMS)	W	± 0.5	± 10.0	± 4.5	± 9.0	± 9.0				± 9.0
AHU Flow Rate	CFM	± 6.1	± 12.1	± 36	± 85	± 85	± 36	± 85		± 85
Atmospheric Pressure	kPa	± 0.03	± 0.3	± 1.0	± 1.0	± 1.0				± 0.05
Calculated Variables	Units									
Superheat	F	± 0.33	± 1.02	± 0.50	± 1.61	± 2.32	± 0.50	± 3.20	± 3.92	± 1.56
Subcooling	F	± 0.36	± 1.09	± 1.00	± 1.68	± 2.74	± 1.00	± 3.20	± 4.19	± 1.51
Condensing Over Ambient	F	± 0.19	± 1.90	± 0.79	± 1.00	± 2.74	± 0.70	± 2.74	± 3.11	± 1.51
EER (Total)		± 0.20	± 2.17	± 0.39	± 0.95	± 1.69				± 1.46
EER (Sensible)		± 0.03	± 1.04	± 0.15	± 0.38	± 0.78				± 0.77

Table 5. Instrumentation Uncertainty[100]

Table 5 column headings are defined as follows:

- Lab: the minimum and maximum uncertainties found in laboratory measurements for each variable from three sources: PG&E, Intertek and Purdue University Herrick Laboratory.
- EM&V: the field minimum and maximum uncertainties for each variable from KEMA (2010) report's measurements and Robert Mowris.
- AEC 2004: the specification for the 2006-2008 RCA programs.
- VSP: the field minimum and maximum uncertainties for each of the instruments actually used in the program as provided by the VSPs.
- Contractor Current: the accuracy of instruments typically used by contractors in the field as assessed by AEC 2006.
- Revised AEC 2010: the proposed recommended by the 2010 Technical Forum.

From Table 5 we can see that lab measurements are more accurate than field measurements, and that the EM&V measurements are more accurate than the measurements made by VSPs. Some

[100] Robert Mowris comments on the 112310 draft of the Study submitted to Brett Close, SCE and further work with the Study team provided a thorough review and improvement of this table.

VSPs are not meeting the program specifications, and the instrumentation typically used by contractors currently has a high degree of uncertainty. The Current Contractors column does not apply to contractors working with VSPs that require instrumentation that meets or exceeds the AEC specification. The problem with EER uncertainties is that the impact of measures is often less that the uncertainty of the one-time measurement. This can be addressed by monitoring, as discussed later in this report.

7.2 Uncertainties in EER Calculations

In the "Calculated Variables" section of Table 5 it can be seen that superheat and subcooling uncertainties are dominated by the respective Liquid Line and Suction Line temperature measurements as shown that for the Revised Specification 1.56 and 1.51 are essentially the same as the temperature uncertainties of 1.5. Referring to the Robert Davis report, it indicates that the error is twice as high at 7%.

EER and sensible EER uncertainties are more complicated since moisture in the air stream, power consumption and airflow are included with air temperature changes. Moisture can be measured in three different ways, all of which have their own challenge and uncertainties. Field measurement of dewpoint is not feasible but is the preferred method in laboratory settings. Digital readout relative humidity (RH) instruments are common and reasonably priced; although these sensors have accuracy issues and tend to drift over time. Wet bulb temperature measurements are made with a wet cotton sock over a temperature probe which can be a thermocouple, a mercury bulb thermometer, or a resistance thermal detector (RTD). The sock must be kept wet and airflow is needed to keep evaporation maximized. Measurement of supply air moisture is difficult because most methods lose accuracy when RH is over 90% which is the normal condition.

As shown in the Range of EER Lab Test Data (Figure 9), when a collection of hundreds of laboratory tests is plotted the result is a broad range of EER values from a high of over 120% (or 12 EER) to a low of around 40% (or 4 EER). As shown in the far right column of Table 5, an achievable and practical EER field uncertainty of ± 1.47 is the result of using instruments that meet the revised 2010 AEC Tech Forum proposed instrumentation specifications[101]. Tests done by Intertek in March 2010 under the direction of Robert Mowris produced EERs in a range from 3.2 to 11.2 with uncertainty of ±0.20. In the field with an uncertainty of ± 1.47, this would produce an EER uncertainty of 50% at 3.2, the low end of the range. The uncertainty improves to 13% at the high end of the range. The average change in EER over 40 laboratory tests is 0.9 which is less than the uncertainty in measurements made in the field with instruments meeting the revised specifications. This uncertainty of in-field determination of total EER and sensible EER makes a onetime determination of system performance suspect, especially given that improvements from fixing system faults, as measured under ideal laboratory conditions, do not rise to the 20% level. With monitoring, these gaps in uncertainty can be reduced with an analysis of time-series data that has been collected on an actual HVAC system.

The two analytic techniques used to address this type of data are *generalized additive models* (GAMs) and the calculation of autocorrelation functions (ACFs) for each of the lower level

[101] These are proposed and must be subjected a full review by stakeholders before they can be made final.

(directly measured) variables. When the data are presented as a time series $X(t)$, an observation will consist of the overall trend (i.e., the mean, which varies across time) and superimposed measurement error:

$$X(t) = \mu(t) + \varepsilon(t)$$

Where: $X(t)$ is the time series of observations
$\mu(t)$ is the mean value of the observations
$\varepsilon(t)$ is the measurement error or uncertainty

The standard deviation made with the delta method calculation is the standard deviation of $\varepsilon(t)$. It is estimated for the time series by first estimating the temporal trend $\mu(t)$ and then subtracting it from the observations. A GAM is a statistical technique that estimates the trend using spline function methods. Spline methods convert the time series of data into a chain of data segments connected by "knots" estimated by a best-fit polynomial (often a third-order function) making the time series a series of piecewise cubic functions. The standard deviation from each polynomial generates a new data set of standard deviations, in which we would look at how these deviations are correlated (auto-correlation factor) with each other. Spline methods can be used to estimate smooth functions with a high degree of accuracy, but when the length of the time series becomes too long, the degree of complexity required for the spline function increases greatly. In order to characterize a measurement taken over a long period of time, a more complex function needs to be created to account for all the external affects that influence the measurement.

Sensor accuracy is determined by the deviations under repeatable measurements. Applying the time series analysis reduces that uncertainty by characterizing the repeatable error. The analysis uncovers and separates bias error from repeatability. We can never reach 100% accuracy, but by noting how the sensor behaves over time, we can reduce the over-estimated published accuracy down to how the sensor, under a set of conditions, performs. For example, a thermocouple was monitored for 2 days, collected by a data monitoring system logging average temperatures over a 15-minute interval. The published accuracy of the device was 1.8 °F. A spline fit of 4 degrees of freedom was calculated, and the root-mean-square error was observed to be 0.21 °F. The graph of the residuals or deviations from the norm plotted in Figure 14 shows the errors estimated after the systematic effects are taken into account, such as diurnal trends. The ACF plots show very little additional structure to the errors, suggesting that 0.21 °F (range of shaded area) error is a more appropriate value to assume for the uncertainty associated with the thermocouple. The upper left hand graph shows the residual values, or difference between the spline function estimate and the actual measurement over the time period. A well defined spline would account for any trends in measurement, and the chart of the residuals would not show any strong trends itself allowing non-steady state conditions to be analyzed. The next three figures examine the deviation of the current measurement when compared with a measurement of some time past, called the Lag where, for example, the value at 5 is the standard deviation at 5 time steps prior to the current measurement.

We see that the measurement is stable over time, and we can reduce the error in the measurement to 0.21 °F, the magnitude of the shaded area above and below the horizontal axis. ACF, the y-axis of the upper right hand figure, stands for "autocorrelation function" and indicates whether or not there is a re-occurring cycle in the measurement error. In this example there is no cycling occurring. PACF, the y-axis in the lower left hand figure, stands for "partial autocorrelation function" and essentially removes the short lag correlation from longer lag estimates[102]. IACF, the y-axis of the lower right hand figure, stands for inverse autocorrelation function.

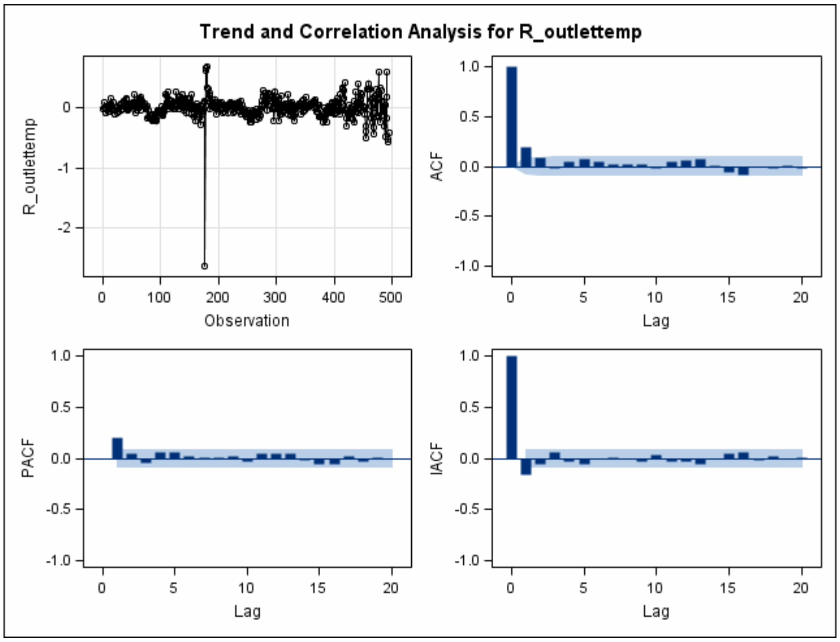

Figure 14. Time Series Analysis Results

Using this analysis to guide further research, it might be the case that if all measurements experience the similar 80% reduction in uncertainty, uncertainty in the field EER measurement could be as little as ±0.29 (assuming 80% reduction in the Tech Forum revision to the AEC 2004 standard Table 5). It is important to remember that this is a simplification of a complex situation.

A practical consideration is how much data on an individual unit would be needed to perform this analysis and achieve an accurate accounting of savings based on change of EER prior to and after maintenance and repair services. It is important to note that excessive data could lead to a miscalculation of uncertainty, by making it mathematically more difficult to estimate the trend. The error extracted from the time series analysis will include any trends that are not accounted for in a weakly defined function. If the time series is unreasonably long, a spline that is computationally reasonable will not entirely capture the systematic trend in the data. This will have two repercussions for the calculation. First, the standard deviation of measurement error will be overestimated, since the unexplained portion of the temporal trend will be superimposed on the measurement errors. Second, there will typically be a strong lag of one time step

[102] The PACF looks for correlations that are unique to a given lag, after adjusting for the correlations that propagate due to shorter time lags.

autocorrelation in the errors from this analysis, which again reflects the superimposition of an unexplained trend.

There are three approaches to minimize this problem. One is to increase the complexity of the spline function by adding more knots. In a spline with “k” knots, estimating the function will take up approximately 2 times “k” degrees of freedom. The second would be to analyze the first (lag one) differences in the time series, which should remove most of the long-term trend but which would double the residual [103] variance and thereby the estimate of error. The last approach is to reduce the portion of the time series that is used to estimate the measurement error. The choice among these approaches would be made based on the amount of data available and the smoothness of the long-term temporal trend.

The following considerations will come to bear when answering the question using a data set that is representative of the equipment being measured. If the time series gets too long or has too complex a trend, then the spline method will become “too computational.” The first difference method will cancel out most of the temporal trend (since the value of the trend at one time point is essentially the same as the trend at the next time point) and allow for the retention of as much of the data as possible. Whether first differences will work depends on how rapidly the trend changes, relative to the sampling frequency. Solid estimation of variance does not require massive amounts of data; the benefit of additional data decreases sharply after approximately 100 data points. For that reason, when the time series is long and one is reasonably assured that the system is operating under steady state conditions (so that the estimated accuracy will be constant across the duration of the series) then you can apply the spline approach to an excerpt taken out of the time series.

A residential scale air conditioner is deemed to reach equivalent steady state in 15 minutes of operation after which a valid set of superheat and subcooling measurements can be taken. If 100 data points are needed and they are taken on a 1 minute interval then steady state operation needs to be continued until 115 minutes have passed. In real-world applications with cooling equipment that is oversized even at peak conditions, two hours of operation will rarely occur except under the most extreme heat spells. This makes it necessary to perform a field study to determine if a set of separated periods of steady state operation can be aggregated into a data set of 100 points. If this is not possible other methods will need to be developed such as ways to force the two hours of operation. The field study would also generate the data and experience needed to explore the validity of using other methods such as the one developed by Anne West and discussed in “The Field Hand and the California Model: An Example of Blending Operational Measurements with Performance Models,” 2010 ACEEE Summer Study Proceedings.

8 Uncertainties in kWh Calculations

The development of computer models to predict annual energy consumption using hourly simulations and weather data that represents an average year goes back to the 1960s. With the

[103] p. 2-328, West, Anne and Mike Logsdon (The Cadmus Group, LLC), Howard Reichmuth, PE, and Jarred Metoyer (KEMA), “The Field Hand and the California Model: An Example of Blending Operational Measurements with Performance Models,” 2010 ACEEE Summer Study on Energy Efficiency in Buildings.

advent of performance-based codes like Title 24 computer models have become relied on and determine whether a building can be constructed. Simulation is simplified by adopting standardized occupancy, lighting, thermostat and other internal gain scenarios. These can be reasonable but are claimed to be the average. The impact interactions between schedule assumptions and building systems are thought not to impact the calculation of the difference in annual energy use between the proposed and standards building because they are the same except for key components like HVAC efficiency. Accuracy of simulation programs are measured by the degree that they vary from the benchmark program.

Section 6 discusses the difficulties in moving from EER measurements to estimates of annual kWh usage. The analysis of measurement uncertainty presented in Section 7 points to problems with one time measurement accuracy. Even if it were possible to obtain unbiased pre- and post-service EERs the "measured" improvement in EER would not have desired statistical significance, and more importantly would not provide a solid basis for quantifying the ultimate goal: annual energy and peak demand savings. Even though the algorithms and performance maps have proven suited to the tasks of standardized ratings and practical design of HVAC systems there is no definitive study of uncertainty.

A significant effort was taken by Koran, et al, to calibrate DOE-2.1C to site-monitored data. The authors concluded that they "were able to successfully tune the DOE-2 model to monitored data…so both tuned models estimated annual HVAC energy use within 11% of the monitored consumption."[104] There is no claim made concerning the uncertainty of the model. The paper provides the reader an understanding of the number of difficult steps needed to "tune" the models to come within acceptable ranges. "Inputs are adjusted, within reasonable bounds, until the simulated and monitored HVAC energy uses are within the following limits: each month ±30%; and seasonally ±20%."[105] Other inputs were also adjusted to the point that abnormally high insulation values had to be assumed. It is not a critique of the approach or its implementation to note that the accuracy of the simulation model cannot be definitively established.

Five increasingly detailed levels of tuned simulations were performed by Alerez and Faramarzi using data from six buildings in the SCE service territory. Level 1 simulations used building-specific data for the inputs to the model. "Absolute estimation errors for HVAC End Use Intensity (EUI) ranged from 1 to 27 percent."[106] The average error was 17.8%. Level 5 reduced the average error in HVAC EUI to 11.6% and "three buildings had reduced absolute errors and three had increased absolute errors"[107]. In this study the inputs to DOE-2 were not modified to the extent undertaken by Koran. Level 2 used monthly kWh and kW data such as would be available from utility bills. Level 3 modified HVAC schedules and inputs based on highly detailed surveys of the operation and maintenance at each site. Level 4 used whole building hourly energy use data and finally Level 5 used load shapes derived from detailed monitoring of

[104] p. 3.175, Koran, W. (PECI), Kaplan, M. (Kaplan Engineering), and Streele, T. (BPA), "DOE-2.1C Model Calibration with Short-Term Tests versus Calibration with Long-Term Monitored Data," ACEEE Summer Session, 1992.
[105] p. 3.167, Koran 1992.
[106] p. 2.14, Alereza, T. (ADM) and Faramarzi, R. (SCE)," More Data is Better, But How Much is Enough for Impact Evaluations?" ACEEE Summer Session , 1994. EUI is end-use intensity in kWh/sq.ft.
[107] pp. 2.17-18, Alereza 1994.

lighting. It would be of great value to go back to these buildings, re-establish the base line HVAC consumption, make improvements to the HVAC systems and then monitor and simulate the impacts of the improvements.

In parallel with the development in hourly simulation modeling an alternative approach based on kWh, kW, and Therms measured at the utility meter has been developing. Nonintrusive Appliance Load Monitoring (NALM)[108] uses metered data with an inventory of appliances to calculate annual energy use of each appliance. In the early 1990s researchers developed and patented specialized monitoring devices that could be installed without shutting off the building power. Insight into the functionality of NALM is presented in "Non-Intrusive Electrical Load Monitoring, a Technique for Reduced-Cost Load Research and Energy Management", in which the authors discuss "recent results from a field test of the non-intrusive load monitor (NILM) as applied to the residential sector, followed by a report of ongoing research that focuses on the commercial sector."[109] With the implementation of smart meter technology every building has detailed hourly and sub-hourly data; NALM implementation is possible on every building. Research will be needed to develop how to analytically recognize the energy use of each type of appliance without the super-fine profiles generated by the devices discussed in the 1992 paper. With this done, research can then focus on developing the software needed to output the breakdown by end use of energy use hourly, daily, monthly and annually at a site. It is then a matter of data analysis to aggregate a large number of sites to derive new level of understanding on HVAC and other end uses. Powerful statistical methods could be used to support energy efficiency program development, implementation and EM&V. As a matter of standard practice customer privacy would be protected and when needed permission would be procured from customers to assess pre and post energy use. Web-based monitoring that is separate from smart meters could add value by giving information to customers that they or their QM contractor can use to save energy and reduce peak demand permanently. It will be worth the efforts of a task force of stakeholders to work out the complex issues of how to make "universal" NALM work to the benefit of customers who will be faced with increasing economic pressure to control peak demand.

9 Other Uncertainties

Evaluating the impact of various HVAC maintenance measures and determining areas for improvement requires the ability to accurately assess before-and-after energy use and then trace the results to specific factors. Unfortunately, this is harder than it sounds. There are a wide range of factors that affect how much energy is saved and how accurately those savings can be measured, and there are many potential sources of discrepancy between expected and actual energy use. These factors include program design, human factors, measurement errors, type of equipment serviced, and maintenance procedures, among other factors.

[108] See http://www.georgehart.com/research/nalmref.html for a current through 1995 reference list compiled by George W. Hart, one of the leader in the field.
[109] p. 3.187, Norford, L., Tabors, R. (MIT), Byrd, J., Philadelphia Electric Company, "Non-Intrusive Electrical Load Monitoring, a Technique for Reduced-Cost Load Research and Energy Management," ACEEE Summer Session 1992.

In this section, we examine the factors beyond instrumentation that complicate efforts to assess the effect of HVAC maintenance measures. Where relevant, we will discuss how these factors may have affected the DTS and RCA maintenance programs' results.

For an HVAC maintenance measure to be successful, it must meet four consecutive requirements:

- **The measure must have the potential to save energy in the field**: The first requirement is that the maintenance measure must be designed and implemented in such a way that it could actually produce energy savings in the field. While this sounds straightforward, it depends in part on being able to accurately predict the effect of the maintenance measure from both a technical and human-factors standpoint, which is often difficult. It is important to distinguish this case from the next because it will determine whether more effective solutions should be sought primarily in the lab or in the field--or in a conference room.

- **The potential savings are achieved in the field**: Even when maintenance measurements have been designed such that they demonstrate energy savings in simulations or in the lab, the same benefits are not always achieved in the field, for a variety of reasons, including field installation anomalies, instrumentation shortcomings, technician training, human factors, deviations from average weather, etc. Better understanding of the frequency and magnitude of various faults in the field is essential in achieving better program design.

- **The achieved savings persist over time**: For long-term savings to be achieved, the measure must yield effects that persist over time. It is possible that a measure could save energy initially, but by the time the evaluators measure its success, the savings have degraded. Another scenario could be a measure that degrades over time, and, therefore, requires retro commissioning or better QM. Lack of persistence is a different problem than a failure to achieve savings at all, and must be addressed separately.

- **The persisting savings are measured by evaluators**: Finally, if savings are achieved and are persistent, they must then be accurately measured by evaluators. There are a number of factors that can affect the accuracy of these measurements.

At each of the four steps, there are multiple factors that affect whether the condition is met. These include human factors (for both contractors and customers), EM&V techniques, and quality control. We will examine each of these in the context of the four conditions above.

9.1 Human Factors

While HVAC maintenance is primarily a technical service, the service is provided by people who work for other people, and is performed for people who own and occupy the building--all of whom may behave in ways that help or hurt the success of the program, as discussed below.

A maintenance measure is only effective if technicians have the tools, skills and training to implement it properly. While the maintenance tasks themselves may be quite simple to accomplish, the technician (or automated diagnostic tool) will need to exercise significant judgment in evaluating the data and the condition of the system and deciding whether it makes sense to proceed with maintenance, which tasks to perform, and how to perform them and verify the effectiveness. Technicians need to have access to appropriate training classes that prepare them for the diagnostic and remediation tasks. Even when technicians are well trained, however, they may not be given enough time to complete the necessary tasks at the job site because their employer (the contractor) requires them to make a certain number of calls per day. The contractor's business model can be a limiting factor in the potential for savings. Anything that can be done to change the contractor business model-- e.g., by encouraging customer demand, reducing customer call-backs, or increasing the contractor value related to this type of service--will help in this regard.

Assuming that maintenance measures are achievable in the lab by someone with a typical technician's skill set, actually achieving savings in the field is primarily in the hands of the specific technician performing the work, under the constraints imposed by his employer. That is, assuming the technician can do the work, the question becomes whether they will do the work properly. The likelihood of high-quality work is affected by several factors:

- Does the technician know the required processes?
- Does the technician follow the specified processes?
- Is the technician's work of high enough quality that mistakes and errors are minimized?
- Does the incentive structure offered by the utility provide sufficient motivation to the contractor/ technician to do the work?
- Does the technician have the instrumentation and other tools that are required for providing the service?
- Has the technician calibrated his or her instruments?
- Is the technician cheating and/or cutting corners?

Success here requires training, process specification, quality control, and program support, such as variable incentive levels reflecting different levels of performance, and specification of tools and calibration for ensuring quality installations. <u>Technicians</u> affect the persistence of savings, through their attention to detail and the comprehensiveness of the service they provide.

<u>Building owners</u> can also have a significant impact on the persistence of savings, by choosing to perform (or not) routine maintenance such as replacing filters, and should be taught the basic necessary system maintenance requirements.

Other behavioral challenges can be harder to overcome. Many <u>occupants</u> will "take back" a fraction of the savings from a measure by increasing their comfort level (and HVAC energy use) once the system is operating more efficiently. Educational materials can help mitigate this effect.

Accurate savings measurements require cooperation among multiple program participants. The occupant or owner must provide access to the <u>EM&V specialist</u> to allow the measurements to be taken, ideally both before and after the service is provided. Unfortunately, occupants are often unwilling to grant access to the building. Technicians can play an important role in ensuring that access will be granted (e.g., by working in the evenings and weekends for the convenience of owners). Measurement and verification plans should allocate sufficient time and resources for pre- and post-service measurements to be taken in a timely manner, with accurate and calibrated instruments. Ideally, measurements should be based on time-series monitoring. A challenge here is that measurement technicians are often under the same time and instrumentation constraints as HVAC technicians. Technicians should be trained to understand the importance of careful, accurate measurements, so that they are more likely to avoid errors and obtain reliable savings estimations.

It is also important to design programs with an appropriate accountability structure. The description that follows is a composite of stakeholder input presented without attribution to respect the proprietary and competitive interests of those who gave input.

The concept of a Verified Service Provider (VSP) was developed in the late 1990s[110] as part of what is now known as a 3rd party program. A 3rd party program is one administered by a third party on behalf of the utility, rather than directly administered by the utility. In support of competition, RCA and DTS programs for 2006-2008 were structured as a "core" or "mass market" program administered by the IOUs. VSP services were offered by a handful of companies each of which has a different business model. IOU program policies and procedures required VSPs who met the program's requirements to sign contracts with IOUs. VSPs then could implement the RCA program by recruiting contractors, training technicians, providing a database of their activities in support of invoices for incentive payments, and conducting Quality Control (QC) on the work being done. One result was that when IOUs, or their implementation contractor hired by them, took over the administration the responsibility for results and QC responsibility became blurred. The administrator and VSP were both conducting QC with the money set aside for the effort. Because the VSPs competed for contractors and technicians it was not in their interests to be overly aggressive in their QC efforts. Contractors and technicians tended to gravitate to the VSP that was perceived as having the best ratio of incentives paid to work required. It is reported that contractors and/or technicians could be pushed out of one VSP and then sign up with another. It is the perception that this trend toward only meeting the loosest interpretation of the program specifications led to the rise of what has been called "program contractors" or "rebate chasers" instead of contractors who used the RCA and DTS programs to grow their business. This led to a level of mass production that worked well for apartment complexes where the utility bill-paying tenants were not aware that the service had been performed, which had negative EM&V results. For this type of contractor there was disincentive to establishing long-term relationships with customers since that would take time away from doing more jobs. There are immediate solutions to these programmatic problems if the focus is on aligning incentives and self interest with program goals. A measure can be cost-effective but can then be rendered ineffectual and not cost-effective by the program implementing the measure in the field.

9.2 State of an Air Conditioning System

The specific air conditioning system being serviced affects the estimated and measured energy savings, and their persistence. The range of absolute savings from one unit to another can vary by an order of magnitude due to the mechanical status of each unit and, especially in residential applications, the behavior of the occupant. Maintenance programs must walk a fine line between providing a mass-market approach that is easily managed, and a specialized approach that addresses each individual system on a custom basis. The development of a measure that is a

[110] Proctor Engineering Group ran a pilot program funded by PG&E in the late 1990s called CheckMe.

probabilistic package of technician QM activities or treatments shows promise. An example of this is Expected Value Analysis, which uses probabilistic decision theory to generate the likely composite package of treatments. Each individual site will have the service done that is appropriate but when all sites are assembled the QM measure is the weighted average of treatments which have been performed.[111]

Some systems can be more difficult to measure than others. For example, direct measurement of system airflow can be easy with a flow plate in a return air filter grill. But other systems such as larger RTUs have higher airflows than can be measured by flow plates, and would require the expensive services of a certified Testing, Adjusting and Balancing (TABB) technician if a certified measurement of airflow is required. Without direct measurement of airflow EER calculations become even more uncertain. ACCA Standard 4 has the technician check for access problems so that the owner can be advised. Sometimes clearances do not meet manufacturer's specification or building code requirements. A myriad of field configurations exist in the field where over 10 million units are waiting to have QM services.

Ideally, there are some units that should be replaced rather than serviced. All mechanical equipment has a unique useful life and DEER uses 15 years[112] when analyzing HVAC equipment. As shown in Figure 15, over 30% of California air conditioners are at least 14 years old, suggesting that a significant number of these units should likely be replaced or undergo extensive repairs rather than be serviced. Every year millions of units fail, often because the compressor burns out. In the past it was common, in the case of split systems, to replace the condenser unit which contains the compressor. But when this is done current Title 24 requirements are not met because an AHRI certified system, condenser and evaporator, is not being installed and thus the required minimum efficiency of 13 SEER can not be verified. An additional problem is that manufacturers have switched refrigerant and existing evaporator coils may not work with the new, higher pressure refrigerant making it necessary to replace both the evaporator and condenser. This further increases the cost of the replacement and triggers additional Title 24 requirements. Installing a new compressor is a "repair" and does not trigger Title 24 requirements. As noted at the Technical Forum, compressor manufacturers have seen an increase of replacement compressor sales to contractors which is thought to indicate that technicians are replacing compressors more often. .

This replacement or refurbish on burnout (ROB) scenario still presents the technician with a diagnostic problem because the service call is usually triggered by discomfort from a unit that is not blowing cold air. While some compressors are obviously burned out there are other situations where diagnostics must be performed to isolate the problem. Most refrigeration systems have several concurrent problems, such as a degraded compressor, dirty condenser coil, high charge, and a liquid line restriction, which in combination cause failure but which individually are not catastrophic. Fixing one of them could get the system back to producing

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[111] Hart, R. et al., "Expected Value Prescriptive Savings Method," in *ACEEE Summer Study 2010; Poster Presentation Handout* (presented at the ACEEE Summer Study 2010, Portland Energy Conservation, Inc. (PECI) and Energy Trust of Oregon (ETO), 2010), www.peci.org/resources/commercial-retail.html. http://www.peci.org/documents/ACEEE_EV_Handout.pdf; also, http://www.peci.org/documents/rtuPremVent_ShortTermRpt09.pdf

[112] http://www.deeresources.com/deer0911planning/downloads/EUL_Summary_10-1-08.xls

cool air however inefficient it is operating. Fixing all of them could restore efficiency but can be more expensive than installing a new system particularly when the unit is decades old.

If multiple faults are present, standard refrigerant-charge–adjustment-only processes have a limited potential for savings. Given the potential for multiple faults and their impact on the potential for savings, a standard procedure or protocol is needed to support the technician efforts. An example of this could be the troubleshooting guides that manufacturers provide in equipment installation manuals. Part of this type of guide would be a decision flow chart that would facilitate the discussion between the owner and the technician about needed repairs. It is always the case that it is the owner who decides to spend the money to repair or replace the system and in the present recession the least cost approach dominates the discussion. The decision flow chart could help the customer to make the best realistic choice. Low cost financing with large incentives will help make replacement affordable. But, if the owner decides not to do extensive repairs or replace the system it can still be the case that RCA or DTS is worth doing.

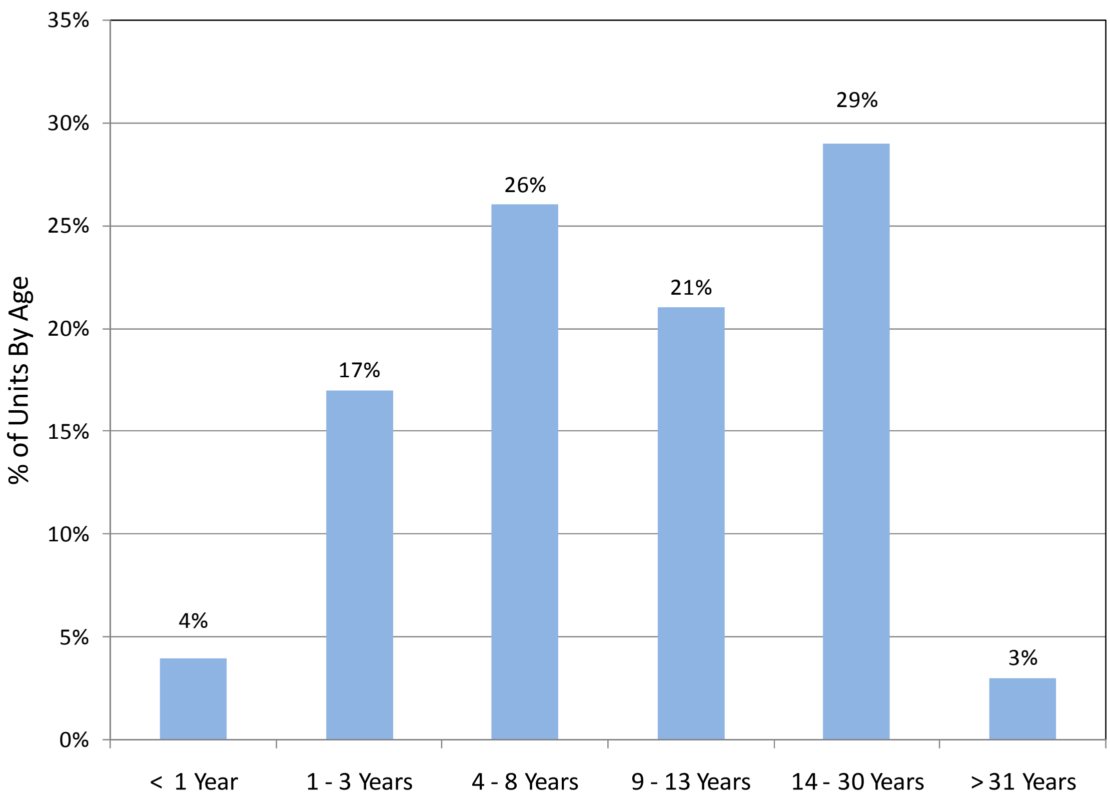

Figure 15. Age of California Residential Air Conditioning Systems[113]

If a unit and its duct system were badly designed or installed, then HVAC maintenance measures are likely to be more effective than assumed. A common problem is ducts that are too small for the required airflow. Ducts with disconnects and other major, visible leaks can be fixed first

[113] p. 24, Figure ES-23, 2009 California Residential Appliance Saturation Study, Executive Summary, CEC-200-2010-004-ES, KEMA, October 2010.

because they are the dominant cause of system inefficiency. If ducts are inaccessible, then they cannot be adequately sealed using methods that most contractors would employ[114]. If an air conditioner's design or installation leaves little room for accessing a (dirty) evaporator coil, it may be difficult to effectively adjust the charge. If the compressor or other components of the system are malfunctioning, the system cannot be fixed with a standard charge adjustment process making it desirable that the technician on site is qualified to address the problems that are found.

It is possible to service a system, verify that is has no faults, and then have faults develop soon after the service call. For example, if the building occupant removes the filters after the evaporator coils are cleaned, then the coils can quickly become fouled again--especially in homes with pets and floor returns or low wall returns. If there is a leak in the refrigerant line, then simply adding charge will not address the problem and the low charge fault will reoccur. Ducts can be damaged by other home improvement projects or by pests.

9.3 Measurement Uncertainties

The measurements that are taken during air conditioning maintenance are critical to saving energy because they dictate the remediation steps that ideally should be taken. The accuracy of the instrumentation specified for use by technicians under column "AEC 2004" in Table 5 is not sufficient. If the specified instrumentation accuracy is inadequate, then the contractor may be unable to effectively service the system. Highly accurate instruments can support the technician in achieving savings, but the cost and fragility of laboratory instrumentation make them impractical for use in the field. Instrumentation sensitivity and cost must be balanced: how accurate do instruments need to be to attain the desired level of confidence, and what is the most cost-effective way to reach this precision? Advances in digital instrumentation such as digital refrigerant pressure gauges with 1% accuracy instead of the 3% achieved with analog dial gauges are making it possible to require improved accuracy. Regardless of the sensor accuracy, calibration must be done on regular schedule and all too often it is not done at all or is done incorrectly. The current RCA protocol calls for annual or monthly recalibration of instruments, but there is no requirement that the calibration be done with National Institute of Standards and Technology (NIST) traceable equipment using methods that adhere to a standard. It may be too expensive and not necessary to require NIST traceable calibration. A review of accuracy and calibration requirements on an instrument-by-instrument basis can address these issues. The review can also include a detailed description of where and how sensors are to be installed including system diagrams and installation detail drawings.

9.4 Diagnostic and Remediation Process Uncertainties

Even with high-quality instruments, the process used to take measurements and adjust air conditioning systems will determine whether or not savings can be achieved. This process must be effective, efficient, well-defined, clearly specified, and well-carried out.

The definition of a measure and the process used to implement that measure has a huge impact on the potential to save energy. Coil cleaning is a common practice but is not in DEER and was not required by past programs and, therefore, contractors did not receive an incentive for implementing it--so it is often neglected. The cost of cleaning the evaporator coil can be

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[114] The Aerosol sealing technology is sometimes the only option and then there are situations it cannot handle.

prohibitive in cases where it is in a confined space and is not equipped with an access panel yet some would say that it is a necessary part of ACCA Standard 4. This raises the point that Quality Maintenance requirements are not primarily concerned with cost effective energy efficiency but can be the foundation on which persistent energy savings can be achieved. The first complete service will take much longer but is then followed by regular service that keeps the unit working properly. Similarly, the incentive for a duct test and seal service is tied to reducing the leakage rate by either a fixed percentage or below a fixed level. In either case, the incentive structure does not reward contractors for achieving further savings.

There are different ways to obtain and analyze HVAC system data. Without IOU incentive programs technicians use simple checklists to show the customer that the suite of items has been done. At the Technical Forum contractor/technician representatives spoke of the common problem that a technician has little or no historical information on the unit being serviced. This can be the case even when a technician from the same company was the last one servicing the unit. ACCA Standard 4 and 180 (for commercial units) require documentation to address this problem. The IOU RCA programs of necessity require documentation to qualify for incentive payments. Each VSP has its own approach. For example, Verified, Inc. offers a hand-held computer into which the technician enters the relevant instrument readings. This platform determines the target values from a lookup table, compares these with the measurements, and suggests appropriate remediation. Field Diagnostic Services Inc. (FDSI) has a service tool that combines sensors, data acquisition and a sophisticated model to guide the technician's actions. PECI's Air Care Plus uses the FDSI tool to which they have added detailed procedures to diagnose and repair economizers. Enalasys uses a laptop with wireless sensors to record data and guide the technician. CheckMe uses forms and call-in data reporting and computerized expert verification to capture data and guide technicians. These diagnostic tools and methods should be reviewed to ensure that they accurately and effectively identify the conditions that they are designed to detect.

Given the increasing capabilities of mobile computing using smart cell phones with texting, web access, email, photos and even videos it is possible that paper records can be eliminated. The technician uses a device to record data in response to prompts from the device. These data are captured by the device and sent, either concurrently or later when it is linked to its server, while the device continues to guide the service. The technician is allowed to focus their attention, creativity and skills on the equipment rather than having to worry about the process. Uncertainty is reduced but is not eliminated. Further reductions depend on the training and motivation of the technician with the support of the contractor. It continues to be critically important that QC is performed by the VSP because humans will always be able to outsmart machines. In opposition to the trend to depend on machines to reduce uncertainty and error is the experience of CheckMe.[115] They have found that having a technician report data to a person who is backed up by a computerized expert system yields an in-depth QC process. For most people, lying to a real person is difficult especially when that person can immediately know if the data makes physical sense. A suspicious call can be flagged as a job to be field verified. Further work and discussions will be needed to reach consensus on what are the required components of QC. A menu of components could be developed from which a VSP or program can pick and choose.

[115] PEG comments on 112310 Study Draft submitted to Brett Close, SCE.

The foundation has been laid for developing a generic, performance-based protocol that can be implemented by VSPs, instrument manufacturers, and other entities whose business is to support the work of HVAC technicians. The ACCA standards and the experience gained from implementing RCA programs provide the raw material from which Stakeholders can hammer out the protocols. This will be a process that will first be tested in meetings and then be tested in the field. It will not ever be "final" but it can progress in phases making steady improvement as is the case in all standards. It will be desirable that Quality Control, Quality Assurance and Verification be built into the performance-based protocol. Quality Control could allow the contractor and VSP to supervise the work of the technician. Quality Assurance allows VSPs and IOU program administrators to supervise the work of implementing contractors. Finally, verification allows regulatory supervision of the programs. These supervisory activities can then be used to loop back to improve the protocol.

10 Implications of Uncertainty

The uncertainties in measuring superheat, subcooling, EER and kWh in the field (along with other forms of uncertainty) are sizable as shown in Table 5. For this discussion it is assumed that there are no other significant faults or that energy efficiency is improved by doing charge adjustment without correcting other faults. Section 7 described the uncertainties in the instruments that are used, and the factors that are calculated from the instrument[116] readings; these uncertainties based on the self reporting of the various entities are summarized in Table 6 below.

	Lab	Field	
	Herrick, Intertek, PG&E	**2004 AEC RCA**	**Contractor Current**
Superheat °F	+/- 0.33 to 1.02	+/- 1.68	+/- 3.54
Subcooling °F	+/- 0.36 to 1.09	+/- 2.83	+/- 4.21
	Lab	**EM&V**	
EER (Btuh/Wh)	+/- 0.2 to 2.17	+/- 0.95	
kWh/year		> +/- 20%	

Table 6. Summary of Uncertainties in Measured Values and Energy Metrics

The field technician measures superheat and subcooling in order to carry out diagnostics. EER is calculated to characterize savings and estimate kW and kWh reduction.

116 The data from instrument manufacturers are reported at the 95% confidence level although it is not always clear what is the confidence level of the accuracy declared in the product specification. NIST traceable calibration is needed to make sure even though is often an additional cost item.

10.1 Target Superheat and Subcooling

Superheat and subcooling must be measured accurately if we are to have confidence that a charge adjustment will result in energy savings. Figure 16 helps illustrate how the uncertainty in the measurement of superheat and subcooling is evaluated along with the allowed range using the superheat allowance of ± 5 °F (the target subcooling delta is ±3 °F).

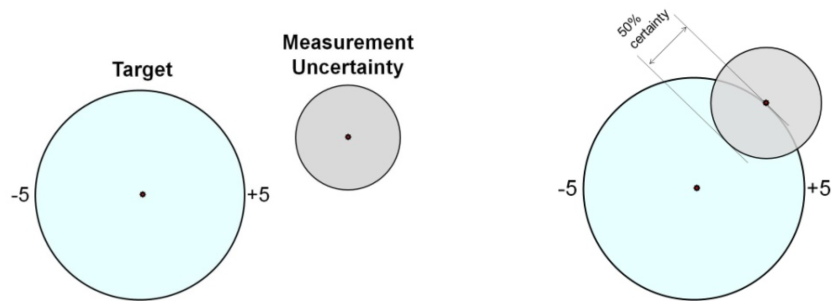

Figure 16. Illustrations of Interaction of Measurement Uncertainty and Measured Superheat

a) An incorrect charge situation is illustrated. For a given Return Air Wet Bulb and Condenser Air Dry Bulb, contractors look up the target superheat in a chart such as that shown in CEC's 2008 Title 24 Reference Appendices[117]. Contractors then measure the operating temperatures and pressures to determine the measured superheat. The contractor subtracts these two to determine how close the measurement is to chart value. In this case the charge is obviously outside the allowed range of chart superheat value.

b) If the measurement is outside the allowed range of ±5 °F, then charge is added or removed until the measurement is within ± 5 °F. Standard practice is to get to the edge of the range and stop, but it is incorrect because the uncertainty of the measurement is not taken into account. No matter how accurate the measurement is the confidence level is 50%. If the contractor stops at this charge level, there will be a 50% chance that the charge will be within the desired range, and a 50% chance that it will not. This means that later verification has the probability of finding the charge incorrect in 50% of the units.

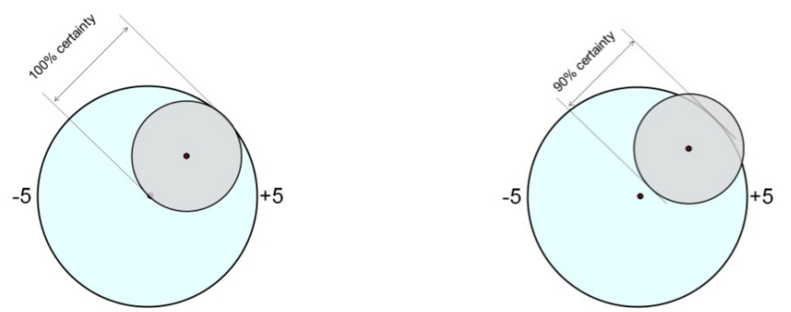

Figure 17. Illustrations of Adjusted Allowed Superheat Range

[117] http://energy.ca.gov/2008publications/CEC-400-2008-004/CEC-400-2008-004-CMF.PDF see page RA3-17.

c) Accuracy does matter in determining how much the contractor must tighten the range technicians must achieve to gain confidence in the measurement. Contractors should aim to get closer to their target. If they continue to add or subtract charge until the value is close enough to the target, then, as shown in the illustration, there will be a 100% confidence that the superheat will be within the required range.

d) But it is impractical to make the exact adjustments to charge needed to achieve 100% confidence. Utilities and the CPUC typically require a 90% confidence interval for factors affecting savings. This allows the range to expand but it is still not at the original ± 5 °F.

e) In order, then, to ensure that the measurement is close enough to the target value to give a 90% confidence in the reading the allowed range must be smaller. The allowed range is a function of the uncertainty in the measurement, and the relationship is:

Measurement Adjusted Allowed Range = (5°F) - (90% Confidence)*(°F measurement uncertainty)

Thus, the allowed range depends upon the accuracy required of the instrumentation. Table 7 shows the Adjusted Allowed range as a function of superheat or subcooling uncertainties, to achieve a confidence level of 90%.

Uncertainty in measured Superheat	Adjusted Allowed Superheat (target – measured)	Uncertainty in measured Subcooling	Adjusted Allowed Subcooling (target – measured)
± 0.0 ° F	± 5.0 ° F	± 0.0 °F	± 3.0 ° F
± 1.0 ° F	± 4.1 ° F	± 1.0 ° F	± 2.1 ° F
± 2.0 ° F	± 3.2 ° F	± 2.0 ° F	± 1.2 ° F
± 3.0 ° F	± 2.3 ° F	± 3.0 ° F	± 0.1 ° F
± 4.0 ° F	± 1.4 ° F		
± 5.0 ° F	± 0.5 ° F		

Table 7. Allowed Range as a Function of Superheat or Subcooling Measured Uncertainty

In order to be 90% confident that a superheat measurement is within ±5 °F, using an allowed range of 5 is not theoretically possible, as it would require an instrument with 0% uncertainty. As shown in Table 6, current contractor instruments typically have an uncertainty in superheat measurements of ± 3.54 °F. Referring to Table 7 and the equation that generated it, contractors would have to come within 1.8 °F of the target value in order to have confidence that the measurement of superheat is within ± 5 °F of the target. If contractors' instruments met the 2004 AEC RCA specifications, then they would have a measurement uncertainty of ±1.68 °F, and would need to be within 3.5 °F of the target. If the Tech Forum proposed specification is met the accuracy is improved to ±1.56 °F then the allowed range is ± 3.6. Subcooling is more difficult because the allowed range is less, ±3 °F. Current contractor instruments measure within ± 4.21 °F which makes it impossible to get the confidence needed. To get 90% confidence with Tech Forum specified instruments the adjusted range is ±1.64 and drops to ±0.45 with 2004 AEC RCA specifications.

This leads to one of two conclusions:

1) An improved instrumentation suite is required to allow contractors to stop when they get within ± 3.6 °F for superheat and ±1.64 °F for subcooling; or
2) With current contractor instrumentation suites, contractors must continue adjusting charge until they are within ±1.8 °F for superheat. Subcooling cannot be measured to the required confidence level.

10.2 Superheat and Subcooling Measurement Instrumentation

Based on participant input at the Tech Forum, the project team proposed changes to the instrumentation and diagnostic protocol. The proposals were discussed but the Tech Forum was not the proper venue to move past the proposal stage. There will not be consensus until further work is done and stakeholders come together to discuss the issues, but it is generally agreed that improvements to the existing specification are needed. Table 8 summarizes the changes to the 2004 AEC RCA specification recommended by the group. Factors in **BOLD** are required and have not changed.

Proposed Revised Specification				
Measured Variables	**Units**	**Accuracy to 95% Confidence**	**Status**	**Calibration Interval**
Supply Air Dry Bulb	ºF	± 1.5	required	monthly
Return Air (Dry Bulb)	ºF	± 1.5	required	monthly
Outside Air (Dry Bulb)	ºF	± 1.5	required	monthly
Mixed Air (Dry Bulb)	ºF	± 1.5	if OAS required	monthly
Supply Air (Wet Bulb)	ºF	± 1.5	required for total EER	monthly
Return Air Wet Bulb	ºF	± 1.5	required	monthly
Outside Air (Wet Bulb)	ºF	± 1.5	optional	monthly
Mix Air (Wet Bulb)	ºF	± 1.5	required if OAS	monthly
Supply Air Relative Humidity	%	± 2 %	required if OAS	monthly
Return Air Relative Humidity	%	± 2 %	required	monthly
Mixed Air Relative Humidity	%	± 2 %	required if OAS	monthly
Suction Line (Dry Bulb)	ºF	± 1.5	required	annually
Liquid Line (Dry Bulb)	ºF	± 1.5	required	annually
Suction Pressure/Temperature	psig	± 1 %	required	monthly
Discharge Pressure/Pressure	psig	± 1 %	required	monthly
Condenser Fan Power (True RMS)	W	± 2 %	required for EER	annually
Compressor Power (True RMS)	W	± 2 %	required for EER	annually
AHU Power (True RMS)	W	± 2 %	required for EER	annually
AHU External Static Pressure	IWC	± 0.049	optional	annually
AHU Flow Rate	CFM	± 7 %	optional	annually
Duct Leakage Tester	CFM	± 3%	optional	annually
Calculated Variables				
Temperature Split (return - supply dry)	ºF	± 1.52	required	
Superheat	ºF	± 1.52	required	
Subcooling	ºF	± 1.70	required	
Evaporator Temperature	ºF	± 1.40	required	
Condensing Temperature Over Ambient	ºF	± 1.70	required	
EER (Total)	Btuh/w	± 1.47	optional	
EER (Sensible)	Btuh/w	± 1.12	optional	

Table 8. Changes to 2004 AEC Specification Recommended at Technical Forum

Temperature

The temperature accuracy has been kept at 1.5, although it may have to move to 1.8 °F reflecting the fact that 1 °C (1.8 °F) is the normal limit of type K thermocouple accuracy. Better accuracy can be theoretically achieved with RTDs and may be preferred by some but are not well suited to refrigerant pipe surface temperature measurements because of their profile and response time. Sensors are preferred that can be configured like the small bead thermocouple. These must be strap mounted on a cleaned pipe with a thin layer of electricity insulating plastic wrap underneath[118] and insulated on top with ½" foam insulation extending 3 inches on either side of the sensor. Clamp-on pipe surface temperatures were allowed under prior programs but should not be used because they cannot be effectively insulated. Suction line surface temperature must be taken on the top of the pipe to avoid sensing problems (returning oil temperature). Preliminary testing of various measurement techniques at PG&E's TAS lab indicates that more research is needed in this area.

Using Type K thermocouples in free air yields uncertainty levels that are half of the allowed superheat or subcooling range. But by allowing clamp-on thermocouples and thermistors that perform poorly, the uncertainty in the superheat and subcooling values is too high to allow an accurate assessment of whether the refrigerant charge is correct. This is a critical failure in the 2004 specification, because it means that it is very unlikely that technicians will be able to accurately and effectively adjust refrigerant charge.

Humidity

Moisture in the supply and return air streams are generally measured using relative humidity or wet bulb sensors.

Pressure

Digital gauges with 1% accuracy are required. Dial gauges are subject to inaccuracies, erroneous readings, and are easily knocked out of calibration.

Other Diagnostic Data

Five calculated values are required for use with enhanced fault detection and diagnosis algorithms. Temperature split, superheat and subcooling are still used along with Condensing temperature Over Ambient (COA), converting suction line (evaporator) pressure to evaporator temperature, and condenser approach temperature. Taken together these allow for an assessment of the unit.

Optional Data

Optional measurements are listed in Table 8. Mixed air temperature and moisture conditions are used when outdoor air supply is introduced through a commercial packaged unit. Economizers used on packaged units need additional controls measurements and operational testing.

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[118] According to John Proctor the electrical conduction issue is "not based on science. We have extensively tested for electrical interference with thermocouples and found no problems." PEG comments on 112310 Study Draft submitted to Brett Close, SCE.

Compressor power is useful especially when a compressor performance table or map can be used to give additional information about the system.

Calibration

The current RCA protocol requires inspection and recalibration of instruments. Instrument calibration errors cause unpredictable errors in measurement, and make determining the actual system state with any degree of confidence impossible. To address uncertainty, it is important to clearly specify requirements and procedures for the calibration of every type of instrument used in the HVAC programs.

Measurement Methods

Few studies have quantified the effect of using different instrument or measurement methods on the measured values. As discussed in Section 7.1, it is clear that the measurement method that is used can have a substantial effect on the resulting level of uncertainty. There is also the issue of offsets between different sensors which may have good accuracy but be consistently measuring higher or lower than each other thus throwing off measurements such as the temperature split. To address problems of incomplete mixing in return and supply air streams researchers have used averaging thermocouple grids with multiple sensing points spanning the duct cross section. In the field this approach is not terribly practical give access and time constraints.

10.3 Measurement of EER

By definition, the EER is the most significant system variable in determining the energy savings. It is used to characterize the improvements made in a system, and is used in models that calculate annual energy savings. Superheat and subcooling target values are used as metrics for improving the EER of a system but do not directly predict EER changes. They have the advantage of not requiring measurement of airflow or wattage power draw (true power not just amperage) both of which require instruments and methods that are commonly used by service technicians. Looking back at Table 6, we see that the uncertainty in the EER calculation when using laboratory data was from ± 0.2 to ± 2.17 Btuh/Watt-hour, and in the field it was claimed to be ±0.95 for the “max” case. If real improvements in the EER of a system are on the order of 10%, they will be difficult to measure with confidence. If the EER metric continues to be used as the primary method of assessing energy savings, it's important to monitor the quality of the measurements used to generate the EER value.[119]

Based on the values of the sensitivity coefficients[120], the EER calculation is highly dependent on the accuracy of the air flow, air temperature and humidity measurements. Measured values will also vary for the same system depending on the operating conditions. Even with highly accurate instruments, uncertainty, ±0.9 at the high end of the range, reduces the confidence in measurements of small changes in EER.

[119] For California’s hot dry climates EER Sensible is a better indicator of efficiency during peak cooling events since it is sensible capacity that impact the space dry bulb temperature which is what the thermostat controls. The uncertainty of EER Sensible is much lower because measurement of air stream moisture change across the evaporator coil has increased uncertainty when compared to measuring dry bulb temperature.

[120] Tables 2, and 4

Data for EER Calculation

Airflow, true power, and supply air moisture content (wet bulb or relative humidity) measurements are needed to calculate the operating EER. AHRI certification standards allow for a ± 5% range when meeting the required efficiency levels in recognition of accuracies that can be achieved in a lab and the difference that will occur between labs. The main cause of uncertainty is the direct measurement of airflow which is ±7%. Temperature split between supply and return air does not measure airflow but rather indicates whether the sensible cooling across the evaporator coil is adequately matched to the refrigerant mass flow rate. Thus, without long-term monitoring, EER improvements cannot be accurately measured. The proposed instrumentation specification can be used by monitoring installations as the baseline for accuracy, but further work is needed to determine the duration and weather event coverage of monitoring required to approach 5% accuracy in EER.

A proven method of reducing inaccuracies is to take multiple measurements. When single measurements are made, the values are subject to the full uncertainty specified by the published accuracy of the device. Taking multiple measurements and using a time-series analysis can significantly reduce the measurement uncertainties. Time series analysis of a thermocouple measurement at 15 minute intervals for 2 days demonstrates a measurement error of ±0.21 °F versus the stated accuracy of ±1.5 °F. Assuming that a similar reduction can be achieved for all of the measurements, it's clear that using time-series analysis would lead to a better calculation of the EER. Long-term EER monitoring is not recommended, as the resulting data requires more complex calculations (based on spline functions) and can be impractical.

11 Roadmap to CPUC Goals

In reviewing the preceding sections, it is of concern that the uncertainties in measurements made in maintenance services are large, and the savings from current programs are asserted to be small in relation to the uncertainties. We conclude that a holistic approach to both the design and implementation of the HVAC programs with integrated measurement and evaluation methods can reduce the uncertainties and increase the savings, such that investments in expanded HVAC QM programs can be prudent use of rate payer funds. A holistic approach does not necessitate that the program implementing it be complicated, time consuming and therefore cost ineffective. Future programs will build upon the knowledge gained from previous programs to deliver a holistic set of site specific services to achieve significant savings that are needed to meet CPUC goals and which are verifiable.

In this section is an outline of a roadmap composed of four pathways for meeting long-term CPUC goals and presents our recommendations for implementing this roadmap. In the subsequent section the research needed to support the roadmap is detailed. Initially, efforts can be focused on incremental improvements to technician diagnostic and service procedures, with longer-term goals of replacing outdated units and implementing whole-building retrofits. Our roadmap consists of four paths to a holistic HVAC program approach that covers multiple HVAC market, technology, and process issues to be followed simultaneously.

- **Improve Maintenance Diagnostic Procedures: Monitoring, Data Gathering, Screening, Diagnostics, and Adjustment**: An important step towards a holistic HVAC program approach is to improve technician diagnostic processes and provide more comprehensive services that address multiple faults that are likely to exist. Inclusion of demand response with maintenance measures could also enhance positive impacts.

- **Provide Advanced Services: Maintenance, Repair, Refurbishment, and Retrofit:** With improved procedures technicians can competently implement programs that require more than simple maintenance. Included will be HVAC measures that specify more elaborate repairs, retrofits, and upgrades that will yield higher levels of energy efficiency, at a higher cost, while still being cost effective.

- **Replace Old Systems:** New HVAC systems installed to ACCA Quality Installation Standard 5 can reduce consumption and demand by 50%[121]. The improved technician procedures will allow HVAC programs to foster the installation of new systems prior to an emergency situation so that customers have more choices. Additional increments of energy efficiency should be considered to allow for reducing system capacity and peak demand further. Units equipped with On Board Diagnostics (OBD), also known as Fault Detection Diagnostics (FDD), should be required as soon as possible.

- **Implement Whole Building Renovation and Retrofit:** Whole-building renovations and retrofits have the potential to achieve the highest levels of energy savings. Improvements to the building shell, lighting, and appliances reduce the HVAC loads thereby reducing the cost of the HVAC system required by the building.

The remainder of this section describes these four stages of integration in more detail.

11.1 Improve HVAC Maintenance Process: Monitoring, Data Gathering, Screening, Diagnostics, and Adjustment

It is recommended that the Maintenance process be split into three processes: “screening” to determine what should be done; a “tune up;” and “advanced service.” As a first step in a maintenance program redesign, outcomes can be improved by including additional screening diagnostic procedures and data collection. An “interim” maintenance protocol based on ACCA Standard 4 or 180 could be quickly developed with the support of industry stakeholders and executed by a mid-level technician (although a basic level of competence, skill, and knowledge is still required).

Potential elements of this stage include:

- **Instrumentation**. Digital refrigeration gauges required. Calibration protocols expanded and enforced. Technical Forum recommendations reviewed and made final.
- **Data Gathering**. Based on the ACCA Standard, the technician will gather additional system information at the first field visit, including system make, model and serial

[121] While more field testing is needed the Intertek lab testing of multiple faults generated the lowest EER of 3.2, as plotted in Figure 6, Range of EER Lab Test Data, which would be corrected or addressed by applying Standard 5.

number, service history (if available), as well as relevant sizing and operational data. Simple system performance metrics may be measured at this time.

- **Screening**. Technicians conduct an initial screening to determine whether the system should be serviced or replaced, and to determine what diagnostics are needed.
- **Diagnostic**. Programs need to include basic diagnostic procedures that can be readily understood and implemented by mid-level technicians. These procedures should enable the technician to determine whether the system requires no service, a simple charge adjustment and duct sealing, or more advanced measures.
- **Adjustment**. If adjustments are needed, they can be performed at the introductory service call. These adjustments should include:

  - Test and Seal Ducts
  - Clean Condenser Coils as needed based on approach temperature
  - Clean Evaporator Coils as needed and to the degree that is feasible
  - Repair refrigerant line restrictions based on the relationship between superheat and subcooling depending on installed refrigerant metering device
  - Adjust Refrigerant Charge and Airflow with the requirement that systems that are more than 20% higher or lower than target superheat and subcooling targets receive a charge correction.
  - Set a tighter allowance to define when sufficient correction has been made to achieve higher confidence
  - Install Demand Response (DR) Hardware.

- **Monitoring.** Maintenance services would be more effective if contractors and technicians had access to system performance data prior to the service call. These data could come from a customer's "smart meter," from a device such as the TED and Google Power Meter, the g-meter from Enalasys, or other such systems and devices that are entering the market in ever increasing numbers.

11.2 Advanced Services: Maintenance, Repair, Refurbishment, and Retrofit

Technician diagnostics sometimes reveal that the HVAC system requires more than simple maintenance. Some systems require repairs or retrofits, both of which can offer significantly more savings than simple maintenance. It is critical that future programs build upon the knowledge gained so that full service programs can be implemented to achieve the CPUC's Big-Bold HVAC goals.

In repairing a system, it is often necessary to evaluate and address multiple faults or multiple improvement opportunities to achieve higher energy efficiency. However, assessing the need for multiple services and understanding the best order in which to complete these services is not a well understood process, and requires development of an appropriate service protocol. It also requires a technician with more than the average level of experience and/or a computerized data recording and diagnostics tool. In some cases, making one repair facilitates others; for example, if the repair requires the technician to recover refrigerant from the system, then there are several other repairs that can be executed concurrently. If an older system is not operating efficiently, it may be possible to "refurbish" it by replacing individual components (compressor, condenser fan, blower, TXV, etc.) to extend the life of the system and greatly improve its efficiency.

11.3 Replace Old Systems

Systems will be recommended to be replaced during building retrofits when the diagnostic protocols indicate that it is more cost-effective for the customer to replace an aging system than to repair it; spending money to repair old, inefficient systems does not make economic sense. The availability of financing is a key element here and QI programs can facilitate funding by reducing risk that come from systems that do not deliver savings. Replacement can address sizing issues and enable the use of more advanced features, such as:

- **Fault Detection and Diagnostics**: As part of the Fault Detection Diagnostics (FDD) Roundtable held at the WCEC (July 2010), a 'straw man' proposal was presented for discussion to 35 participants from California and around the country including NIST, four major HVAC OEM manufacturers: Carrier Corporation, Honeywell, Johnson Controls and Lennox Industries, along with national retailers Target and Wal-Mart, and California HVAC contractors, and local code officials. The project is providing the information needed to introduce on-board FDD capabilities as a credit in the next version of Title 24.
- **Sensors and Indicators from Advanced Rooftop Unit Project (ARTU)**: In addition, a wider set of performance, maintenance and FDD functionalities were defined in the CEC PIER Advanced Rooftop Unit (ARTU) project[122]. These included a list of required sensors and controller status indicators, along with a wide range of required diagnostics for severe faults (such as compressor failure) and degradation faults (such as dirty condenser coils).
- **Advanced Onboard Diagnostics for Residential HVAC Systems:** HVAC systems are at a place where cars were in the 1960s when a mechanic had no indication of what was wrong. Concerns about automobile air pollution impacts led to the requirement of On-Board Diagnostic (OBD) computers. To adequately address persistent energy efficiency, HVAC systems will need to have OBD. Attendees of the Technical Forum working for manufacturers expressed interest in what diagnostics are needed to support energy efficiency. They did not discuss proprietary specifics but let it be known that they have the capability of providing detailed diagnostics. The industry has replaced electro-mechanical controls with micro-processor controls. OBD specifications would standardize the error codes and delivery interface as was done for automobiles.

11.4 Whole Building Energy Efficiency Renovation and Retrofit

Achieving significant energy savings will require rethinking the boundaries of HVAC and considering it as part of the whole building system. As part of the CPUC's Big-Bold plan, the CPUC and the IOUs are conducting Whole House Retrofit (WHR) programs. The IOUs can expand the concept to include light commercial buildings along with residential buildings. Growing out of a systems approach, the whole building concept is to consider all aspects of the

[122] Architectural Energy Corporation, Final Report Compilation for Fault Detection and Diagnostics for Rooftop Air Conditioners, CEC # 500-03-096-A1, October 2003.

building, especially the interactive effects. As of the third calendar quarter of 2010, this is a rapidly changing and developing part of energy efficiency programs, legislative initiatives, product development and research. It is beyond the scope of this report to delve further into the subject yet it is important that the building as a system of interacting systems be part of the HVAC QM strategic planning and implementation process.

12 Research Plan

In order to pursue the roadmap outlined above, carefully designed and implemented pilot programs with M&V monitoring are needed to establish the potential energy and demand savings from implementing the diagnostic protocol. These programs will initially establish a baseline performance of representative systems as they are found. Residential split systems and commercial packaged units will be included in the monitoring. Long-term, detailed monitoring is required. This will be costly and will require hundreds of sites to be monitored. Additional laboratory testing needs to be part of the integrated research plan. To fully use the data being collected, a parallel effort must be made to develop simulation computer programs or other methods of predicting kWh savings. Subroutines for programs such as TRNSYS, DOE2 and EnergyPlus will need to be upgraded to use the lab and field monitoring data. Finally, NALM protocols need to be developed and become part of the M&V process and used to improve the simulation based predicted savings.

Specifically, studies should include the following elements:

- Definition of Combined Measures
- Screening Tools
- Diagnostic Protocol
- Instrumentation Needs
- Human Factors
- Verification and Program Reporting
- Measurement and Verification
- Training of technicians, contractors, owners, consumers, manufacturers, etc.
- Value of Savings

Several of these might be combined into a few larger studies, since they cannot be conducted in isolation.

12.1 Define Combined Measures in an HVAC Maintenance Program

There is a need for a study to identify what is the most beneficial set of potential measures to offer as part of an HVAC maintenance program. Entries in this list might include all of the measures mentioned earlier in this report, such as standard RCA/DTS measures, demand response, repairs, and energy efficiency retrofits. It is expected that a service that included several of these measures would save substantially more energy (but cost more) than the single measures that have been fielded to date. Data on the benefits of combined measures are sparse, however, so laboratory testing is needed. In addition, more field research is needed to better identify how common various faults are in real systems.

This study could include the following elements:

- Conduct a lab test to firmly establish the technical potential for remediation of the full range of faults, including problems such as coil fouling problems, non-condensables, airflow issues, duct leakage (supply, return, and at unit/plenums), duct thermal losses, duct under sizing, frequency of dirty or overly restrictive filters, condenser fan motor problems, TXV installation problems, blocked orifice issues, charge problems, and evaporator coil circuiting issues, etc. This might be done on a combination of new and old equipment. The results should be reviewed by industry experts, models should be developed, and the technical potential should be quantified through simulations.
- Conduct a field engineering study to determine the full extent of defects, and frequency of individual faults, in existing systems. This would help to shed light on the extent of the full range of problems. This would likely need to be a sizeable study, in which problems are detected and fixed, and savings are rigorously estimated.
- The field test might be done in conjunction with a pilot program, including a large number of homes, and a range of different contractors doing different measures. These measures could include advanced measures such as system refurbishment, retrofits, repairs, and replacement. Savings could be compared by contractor and/or by measure. To the extent possible, the benefits would have to be disaggregated.
- Another way to understand what is happening in the field would be to work with industry groups such as ACCA on a round robin diagnostics test on a number of sites. After the diagnosis by the various methods a full QM would be performed and the systems repaired to the extent possible. Of special concern would be incorrect diagnosis that leads to making the system run less efficiently and/or those that cause damage. The sites should cover residential and commercial units with and without economizers. A task force is needed to sort through how to proceed so that the test is fair, complete and supportive of improvements in diagnostics.

12.2 Create Better Screening Tools

To keep the costs of the program down while supporting high quality work, technicians need a screening tool to enable them to quickly determine where there are potential problems. This screening tool would be able to distinguish the following types of situations:

- System is operating at a reasonable efficiency, and would not benefit from program intervention.
- System could benefit from a coil cleaning, duct test and seal, and charge adjustment, but not much more.
- System may have non-condensables or liquid line restrictions, or an inefficient compressor, and it would be worthwhile to evacuate the system.
- System is a candidate for a retrofit.
- System has too many problems to possibly address in the program. It may be a candidate for system replacement or a major repair job. If the homeowner does not choose to replace the system, it should receive maintenance.

Once the situation is identified, a diagnostic process will be undertaken to identify specific faults.

A research project is needed to further develop these screening tools. An industry group should be convened to develop the requirements for such a tool. The development effort should include field testing of the tools to ensure their reliability. The industry group can also be involved in the field testing. This field test can be done in conjunction with the pilot program described earlier.

12.3 Develop Multi-Measure Diagnostic Protocols

Diagnosing the need for one of many possible combinations of measures will require a sophisticated diagnostic tool or process that is not in existence today. The diagnostic protocol should be integrated with the recently developed Quality Maintenance Standards from the Air Conditioner Contractors of America (ACCA Standard 4) and the American Society of Heating, Refrigeration, Air-Conditioner, and Ventilation Engineers (ASHRAE Standard 180). The standards make clear to owners, contractors, technicians, regulators, lawyers, and others what must be done to maintain HVAC equipment. But there is a wide gap between the standards and normal practice. The Western HVAC Performance Alliance is working to bridge the gap by defining technician tasks. The standards are general and generic, rather than detailed and specific. Detailed technician tasks will help resolve the scope of actions that are listed and allow contractors to price service packages. An expansive interpretation of every action could mean a first-time service would take 8 hours, which is impractical. The diagnostic protocol will specify the scope of the QM activities.

Many existing installations cannot be maintained until the system is refurbished so that it is installed correctly. Standards-based Quality Maintenance programs can help keep a properly installed system working efficiently over the lifetime of the equipment. Quality Installation of Unitary Equipment, ACCA Standard 5, was developed to clarify what must be done to properly install residential and light commercial equipment. Few if any systems have been installed per Standard 5 even though Title 24 has consistently supported detailed sizing, equipment selection, duct design and sealing. Some existing systems are so poorly installed, old, or inefficient that no maintenance should be done until major repairs are made to the HVAC system. The diagnostic protocol develops a decision tree to guide the owner, technician, contractor and energy efficiency program administrator on the best approach. For example, the tree could establish a rule that ducts must be tested and sealed. Then, if the static pressure between the return and supply plenum is more than 0.5 IWC, the duct system must be modified.

A research project is needed to develop a new protocol and test it in the laboratory and in the field; this protocol could follow the model developed by Haorong Li, as mentioned in Section 4. Again, an industry group could be convened to develop the requirements of the tool. During this requirements-setting process, the group can decide whether the development should be based upon existing tools, or start from some other starting point, and whether it should be a proprietary or non-proprietary tool. The protocol should be bench tested, tested with real equipment in an independent laboratory, and tested for feasibility and reliability in the field. This could also be included in the pilot program.

12.4 Instrumentation Needs

As described in Section 11, the original 2004 RCA specifications should be modified to realistically improve the accuracy of measurements. As shown above, even with improved accuracy, the allowed ranges around target values need to be reduced. Table 8 showed the recommendations reached at the Tech Forum, although the final specifications must be the result of a process approved by the CPUC and IOUs. This process should include a survey of current instrumentation needs, an assessment of available instrumentation, and a more detailed statistical analysis.

One additional element that can be developed is a "Consumer Reports" type of testing facility that can test and assess the appropriateness of the tools used by HVAC service people, and identify suitable instruments. This could be developed and funded by industry players, and be sited at an independent testing facility such as Intertek, or a University laboratory such as Herrick Labs (Purdue University) or WCEC (University of California at Davis).

12.5 Human Factors

Human factors have a substantial impact on the likelihood that a maintenance program will be successful. A study of the behavior of several different individuals and organizations should be undertaken to identify these impacts and determine how to maximize effectiveness. Logic models proven to be useful in program design and along with a market model can be used to develop and test how programs and the QM market can be positively impacted.

A field study that documents the activities of field technicians is needed; this study would observe maintenance activities in as natural a setting as possible, preferably as a blind study. This field study could be combined with a "time and motion" study that quantifies how long it takes technicians to perform certain tasks. Findings would contribute to the development of better tools, e.g. an accurate clamp on surface temperature sensor that is self insulating.

A survey of homeowners and tenants would help shed light on the value of maintenance services to consumers. Homeowners could provide information on typical do-it-yourself maintenance, such as changing filters, and help determine what it would take to encourage a homeowner to engage in a service contract. Previous studies have looked at people's level of environmental concern, but have not made the possible connection between maintenance behavior and environmental protection. In the case of commercial owners and tenants, research is needed to determine what approaches are needed to achieve large and persistent savings from QM.

A survey or focus group of contractors would provide information about requirements for a thriving maintenance business, both in terms of what would make it successful, as well as what it would take to attract contractors.

All of these human factors research topics could be studied in the context of a pilot program.

12.6 Verification and Program Reporting

Verification has long been an important part of RCA and DTS services. Because of the structure of the programs, technicians would be in a position to "game" the system if safeguards were not in place. These quality control measures have been developed by the VSPs, and are thought to be generally appropriate. They could be improved, however.

Program designers should determine which verification measures have been used successfully, and create a requirement that would ensure that this level of quality is achieved program wide. Concerns about errors being more prevalent when data from instruments are entered by hand needs to be addressed. With the increasing availability and capabilities of mobile computing, automated data collection is becoming easier. It may help to combine this with the diagnostic process definition, since the tasks undertaken in the diagnostic are the tasks whose quality is to be controlled. Quality control should also be integrated with measurement and verification (EM&V) strategies, since the goals of both activities are similar.

Program reporting is another area where maintenance services could be improved. The data collected in the program must end up in a common database, and data quality must be assured. If long-term kWh monitoring is implemented, it will need to be integrated with the program databases. If these data were reliable, they could be an important part of the EM&V process, as well as providing input to the deemed savings calculations. Customer-facing reports are also an important element in achieving and maintaining savings.

12.7 Evaluation, Measurement and Verification (EM&V)

There are a number of ways that EM&V can be improved, many of which are already known and acknowledged. A study should be undertaken to develop a more appropriate EM&V plan, and to gain industry acceptance of the plan. Providing EM&V on more of a real-time basis will greatly help its effectiveness, and longer term monitoring will reduce uncertainties. EM&V programs should consider providing EM&V specialists with the same training that technicians receive, so they understand the program as well as possible. EM&V should be well integrated with the program delivery, quality control, and reporting that should also be in place.

The key goal of any EM&V program design is to develop a protocol that provides detailed specification of sensor accuracies, installation requirements, and data handling to ensure that reasonably repeatable results can be obtained. Pre- and post- monitoring on a large number of sites is highly desirable to develop a robust dataset quantifying system performance characteristics and sub-metered energy consumption. To minimize errors introduced through sensor variability and human factor installation issues, it is imperative that calibrated sensors remain in place through the duration of both pre- and post-monitoring periods.

As discussed earlier, following the lead of NALM and utilizing the emerging Smart Meter technology and other low cost power monitoring devices is an exciting option for efficiently expanding data collection activities to thousands of customers. For example, the TED 5000[123] provides one power monitoring current transducer, a measuring transmitting unit, and a Gateway that allows compatibility with Google PowerMeter [124], all for under $200. The Smart Meter, TED, and other competing products[125] represent a significant expansion of low cost power

[123] http://www.theenergydetective.com/store/ted-5000
[124] http://www.google.com/powermeter/about/about.html
[125] http://www.greennet.com/consumer/products-services/#gmeter

monitoring options. Dedicated monitoring of the condensing unit electrical circuit over time (see screenshot of real time tracking in Figure 18) would provide quantification of baseline performance and post-measure performance impacts, and potential performance degradation over time[126]. Low cost power monitoring options are becoming more and more common. These tools should be explored in detail, and if proven reliable, utilized to the maximum extent possible in any future utility HVAC programs.

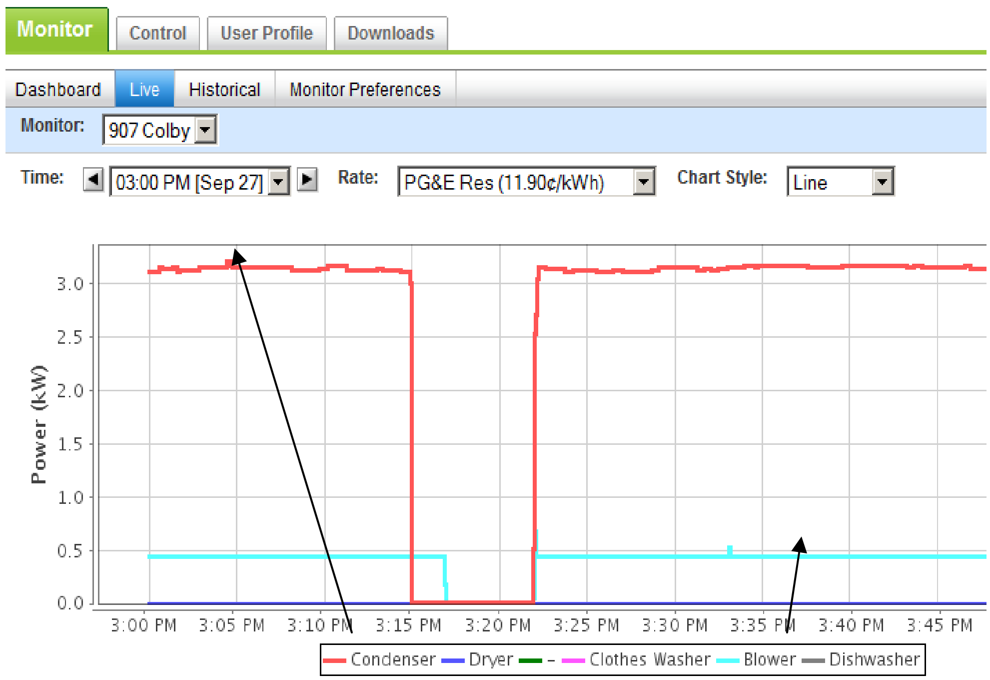

Figure 18. Real-time Condensing Unit and Blower Demand Tracking

Development of the EM&V with NALM and web-based monitoring protocols should occur through a working group that assembles a broad group of stakeholders, in a similar manner to the Tech Forum. Input from national HVAC experts could result in a protocol that would have broad acceptance outside of California. This development effort should include definition of monitoring and analysis procedures and testing of the procedures in the lab and in the field.

12.8 Training Requirements

A set of requirements for training should be developed, with significant input from contractors, technicians, EM&V specialists, and other stakeholders. This should include both the skill set that a technician must have to be an effective service provider as well as the knowledge that the technician has to have to participate in the program. There is also a need to differentiate training for the first QM steps, from the training needed for the advanced services such as repair, refurbishment, and retrofit. It is likely that the training will have to be much more extensive

[126] Optionally monitoring of the furnace electrical circuit could be useful for determining changes in air handler (or heat pump) fan power draw, alerting the owner or VSP for service, which could be as simple as replacing the air filter.

than previously, because the interaction of different measures is much more complicated than single measures. Technicians will have to understand the fundamental operations of the system and have the skills to use the screening and diagnostic tools effectively. Training will be provided by a range of industry stakeholders.

12.9 Valuing the Savings

Transformation of the HVAC industry will require a broadly based, long-term support of QM. In order to get the funding from energy efficiency programs, there needs to be a recognized kWh and kW savings from QM. It is difficult for HVAC measures to be cost effective based solely upon their energy savings especially for residential applications because annual kWh is typically low compared to peak demand. One of the real benefits of programs that affect cooling loads is that they directly attack the peak load. The load factor for cooling in California residential systems is on the order of only about 7%[127], and if only compressor operation is considered then light commercial applications are not much better. The "E3 Calculator," which is used by the utilities to estimate the financial costs and benefits of various measures, may not address cooling-related maintenance measures adequately. The load shapes are taken from the Database of Energy Efficiency Resources (DEER). Because the developing vision of an enhanced diagnostic protocol and QM based on Standards 4 and 180 presented in this report is new, it could not be covered by DEER. Since each site will be unique a probabilistic approach such as Expected Value is needed in place of a rigidly defined package of measures.

13 Conclusions and Recommendations

In this report, we've discussed a wide range of uncertainty driven problems that need to be solved so that the CPUC Big-Bold goals have the possibility of being achieved. The most important conclusions we have drawn from our analysis are as follows:

Uncertainties are inherent in programs such as these and are not well accounted for. There are many interrelated sources of uncertainty, including measurement errors, uncertainties in predicting human behavior, and the compounding effect of performing calculations on imperfect data. Perhaps the most important observation here is that, with the program specifications, methods, and tools commonly used *today*, it is difficult for a simple refrigerant charge adjustment to be implemented, measured, and verified to the level of confidence that is required by the CPUC. It is impossible to eliminate all sources of uncertainty, but they should be mitigated where possible (e.g. if the technician stops when a target superheat or subcooling value is reached there will be a 50% chance that the charge will be within the desired range, and a 50% chance that it will not). A good understanding of uncertainties by program designers, contractors, and technicians is important.

Additional screening and more sophisticated diagnostic/servicing approaches would benefit future programs. Quality maintenance programs have the potential to be successful, but their design and structure could be improved. For example, if technicians perform basic screening of

[127] Annual load factor is annual kWh divided by the kW demand times 8760 hours in a year. For example: 2000 kWh AC consumption divided by the product of 4 kW demand and 8760 hours a year yield a load factor of 5.7%.

HVAC systems to determine whether (and which) services are likely to improve efficiency before implementing charge adjustments, additional energy could be saved. Furthermore, implementing multiple measures can potentially save much more energy than the current strategy of implementing single, simple measures, particularly when multiple faults are present. The costs of providing such a comprehensive service may be higher. However, the additional savings might justify the cost at a large number of sites. The presence of multiple faults and the need for multiple measures complicates diagnostic/service protocols in ways that are not well understood. There is not a thorough, up to date, and independent assessment of the baseline fault conditions of the over 10 million unitary air conditioners in California. Further study would help to develop appropriate diagnostic and service strategies that can be guided by the principles of making sure that no harm is done to the system, that energy efficiency is improved, and that to the greatest extent possible every site visit results in an energy efficiency improvement.

Human factors are significant but are poorly understood. The behavior, motivations, preparation, and constraints on technicians, owners, tenants, contractors, and EM&V specialists can make or break a program. This is an area that has been overlooked in the field of behavioral research, and a better understanding of why people do what they do is critical. If broad CPUC energy efficiency policy goals are to be achieved, the measurement of "free-ridership" needs to be improved to recognize that HVAC quality maintenance measures and services do not exist without the support of energy efficiency programs.

Measurement and verification processes must be improved. EM&V processes and instrumentation need to be improved and integrated with program delivery, quality control and reporting. One-time field EER measurements appear to be of marginal value since uncertainties can approach ±20%. Even with high-quality, time-series EER measurements, there is uncertainty in simulating the annual kWh savings, in part due to behavioral factors affecting occupancy and thermostat patterns. Longer term, broadly implemented pre- and post-measurements of kWh consumption would reduce uncertainty, and could be implemented using utility smart meters and/or web based sub metering.

Over the long term, achieving large energy savings might be possible with replacement of existing systems and integration with whole-building energy efficiency measures. Intuitively, the whole-building approach to energy efficiency should be much more effective than implementing energy efficiency measures in a piecemeal fashion, with the potential to achieve savings of over 50%. Past attempts at this approach have enjoyed limited success. The theory is that a new HVAC system can be sized for the reduced load that results from improvements in ducts, windows, insulation, lighting, infiltration, etc. Equipment kW savings are achieved, although kWh savings are less certain. In the long term, the HVAC industry and utility energy efficiency programs will continue to improve and will likely include providing quality installation, commissioning, automated diagnostics, demand response, and whole-building integration, in addition to maintenance. There will probably always be a need for maintenance-based programs to address the HVAC systems that can become efficient when they receive quality maintenance and the repairs that are needed.

13.1 Recommended Collaboration Strategies

In the course of this research, the authors have identified a number of collaboration strategies that, in the opinion of the authors, would help to move maintenance measures and maintenance programs forward. As part of the development of the Big-Bold HVAC plan a number of productive meetings were hosted by the CPUC. These meetings allow interested parties/stakeholders to participate. This type of collaboration needs to continue especially as generically specified protocols are developed. As demonstrated in the second calendar quarter of 2010, this will at times be a contentious process. Funding will be needed for the research papers, laboratory and field testing required to resolve fact based disputes. Models for these types of collaborative activities are those followed by ACCA and ASHRAE as the QM and QI standards were developed.

- **Work with the Western HVAC Performance Alliance**: Utility companies have already been proactive about working with industry partners to achieve the goals of the CLTEESP by forming the "Western HVAC Performance Alliance" (hereafter referred to as the Alliance). This organization was put together with utility support and significant industry involvement. All of the major industry associations are represented in the Alliance, as well as individual manufacturers, contractors, and distributors. The Alliance is currently forming a set of committees, each focused on one of the goals of the CLTEESP. Utilities should continue to be actively engaged with the Quality Installation/Quality Maintenance committee of the Alliance and any Quality Maintenance subcommittees that are formed. This committee is populated with industry domain experts and thought leaders who bring a great deal of knowledge to the table, which will help ensure that upcoming utility programs are not designed in a vacuum. For example, this report could be reviewed by that committee, and subgroups formed to address some of the key recommendations. Additionally, gaps in accessible knowledge can be filled by funded research. The committee can also be helpful by providing input to program implementation plans for their 2010-2012 programs, as well as the design of their 2013-2015 programs. In addition to that committee, individual members of the Alliance have always been forthcoming with their thoughts and opinions. Conference calls with web conferencing support and/or meetings with key Alliance members would be a very efficient way to get unmatched intelligence on this industry.

- **Sponsor a Short-Term Pilot**: The utilities can sponsor an interim program based upon interim protocols with the cooperation of the CPUC and other stakeholders. While the protocols may not include all of the measures needed to address multiple faults, they should include measures that go well beyond past programs. This could be seen as a pilot for a larger program. As a pilot, energy savings and demand reduction would be achieved but allowances would be approved by the CPUC to allow for exploration of various marketing approaches, incentive structures, and EM&V protocols. An approach could be to fund pilot related overhead separately so that TRC calculations are based on a "mature" program. The pilot could form the stage for human factor research and a test case for advanced measures. This pilot could also serve to support the integration of ACCA Standards 4 and 180 into programs as a way to achieve persistent savings. This pilot would initially be challenged to provide cost-effective savings, but would ultimately provide the intelligence and the confidence for a more extensive program with significant energy and demand savings.

- **Establish and Support a Diagnostic Protocol and Testing Taskforce:** In the meantime, IOUs, CEC PIER, USDOE, and the CPUC could undertake the research studies described earlier in this section. A public process that involves all stakeholders is needed to develop, lab test, field test, and pilot test a new diagnostic protocol.

- **Establish and Support a Web-Based Monitoring Taskforce:** The "game changing" potential of wide spread pre and post energy efficiency activities monitoring needs the support of IOUs as the CPUC regulated energy efficiency program administrators. A vibrant marketplace of web-based technologies has appeared in the last few years to meet the growing and/or perceived demand for better tracking of energy use. Innovation supporting generic data acquisition and reporting protocols can be developed and are needed so that coordination occurs with the smart meter infrastructure being installed by IOUs. Demand response program capabilities can be included in the specifications to improve the cost effectiveness.

- **Policy Changes:** At the same time, utilities, the CPUC, and other stakeholders can work towards making policy improvements. The DEER database needs modification, which is both a technical and a policy problem. Sufficient lab and field studies must be conducted to provide the technical foundation needed to make changes in DEER to more fully recognize that savings from QM and QI are real and can be implemented in the field by qualified technicians. Then a more open process is needed to implement the research results into the DEER to allay the existing distrust of the results. Even more important is having a recognized work paper procedure to calculate the impact of targeted programs for kWh savings with and without demand response. Residential customers with kWh/year usage at double RASS levels (around 2000 kWh/year) may receive enough benefit to achieve cost effectiveness. Even this situation will be problematic if the average cost per kWh is used rather that the 2 to 3 times higher cost of the kWh being saved. With these changes in place, one can anticipate that future cooling programs will be much more extensive and generate greater energy and demand benefits than the current programs.

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Glossary

Compressor
As the primary mechanical component in the vapor compression refrigerant cycle it is has the highest kW demand. The compressor uses an electric motor to compress low pressure/low temperature refrigerant vapor to a high pressure /high temperature condition using reciprocating, scroll or rotary technology. In unitary equipment, the compressor is hermetically sealed inside a container with no serviceable parts.

Condenser
The condenser is the outdoor heat exchanger where heat is rejected to outdoor air that is pulled or pushed through the condenser coil with a condenser fan. The condenser is operated at a fixed pressure temperature as the refrigerant is condensed from a high temperature gas to a hot liquid. Subcooling occurs at the end of the condenser where only liquid exists.

Condensing Temperature and Pressure
The relationship between condensing temperature and pressure is a function of the refrigerant in the system and the system operating characteristics, and current operating conditions. During hot mid-summer conditions, the condensing temperature will typically be 20-30°F higher than the outdoor air temperature.

Duct Pressurization Device
A duct pressurization device uses a calibrated, variable speed fan equipped with a manometer and a flow orifice to accurately measure air flow. All of the duct system outlets are sealed except where the short duct from the fan is attached to the duct system. Fan speed is increased until a specific pressure (typically 25 Pa) is reached as shown on the manometer. Using the calibration charts of the device the pressure and fan speed are converted to air flow. The air flow is the leakage of the ducts at the pressure (25 Pa).

Economizer
Economizers are typically found in commercial rooftop package units. The system includes a damper, motor and controls that allow the HVAC system to either operate in a traditional return air mode, or if outdoor conditions are favorable, utilize outdoor air (70 to100% of system air flow) for low energy ventilation cooling. In dry climates, simple temperature controls can be used; in more humid climates enthalpy controls offer better performance. Economizer technology is starting to appear in some residential equipment. A two stage thermostat or other controls are needed so that the economizer function is used first. An integrated economizer is needed so that if the load is not being met but the outdoor air is still cool the compressor can operate simultaneously.

EER
Energy Efficiency Ratio (Btuh/Watt-hour) is the ratio of the total steady state cooling capacity (in Btuh) divided by the total system electrical demand (Watts). The EER is normally reported at 95°F outdoor air temperature and is a standard performance metric reported by manufacturers

testing to AHRI Standard 210/240 for single phase residential systems or AHRI 340/360 for commercial three phase systems. Confusion occurs when the conditions at which the EER is calculated are not specified and assumed to be AHRI conditions. The Sensible EER is calculated by dividing the sensible cooling capacity by the total power, whereas the rated/reported EER is based on total cooling capacity. As of 2010 USDOE requires all unitary equipment greater than or equal to 65,000 Btuh to have EER ratings from 10.4 to 11.2 depending on type and capacity.

Evaporator Coil
The evaporator coil is the low pressure heat exchanger immediately downstream of the refrigerant expansion device. The evaporation of the refrigerant is driven by the supply air fan, a push through or pull through configuration, which moves warmer indoor air across the heat exchanger. The evaporating refrigerant absorbs heat from the air passing over the heat exchanger.

Evaporator Pressure and **Temperature**
The relationship between evaporator pressure and temperature is a function of the refrigerant in the system, the system operating characteristics, and current operating conditions. During typical cooling operation, the evaporator temperature will typically be 15°F lower than the air passing over the evaporator so that supply air at 55 to 60°F is delivered by a coil running at 40 to 45°F.

Expansion device
A device in the refrigerant system that reduces the pressure between the high and low pressure sides of the system. Typically either a fixed orifice (capillary tube or piston) or a thermostatic expansion valve (TXV).

Fault
An abnormal condition that may lead to system performance degradation or failure is a fault.

Filter-Dryer
A cylindrical component mounted in the liquid line before the expansion valve to capture debris that could clog the valve and to remove moisture. Normal practice especially when a replacement split system is installed.

Fixed Orifice
An expansion valve that is a precision dimensioned tube, piston, or other component that offers a specified flow resistance at a given pressure. Mass flow of refrigerant is dynamically dependent on operating conditions.

IAQ
Indoor air quality is met by introducing outdoor air, except when it is polluted, to a conditioned space to dilute pollutants to an acceptable level. ASHRAE Standard 62 and the California Building Energy Efficiency Code, Title 24, specify the required volume in cubic feet per minute (cfm) need for each person in the space. Carbon Dioxide (CO_2) is used as the control metric for IAQ since is directly related to occupancy in the space but in the case of out gassing from items with in the space it is not always sufficient.

IWC
A measure of pressure in inches of water column where 1 IWC equals 250 Pascals the metric units measurement of pressure.

Latent Cooling Capacity
Represents the energy extracted by the vapor compression cooling system in the form of moisture condensed from the return air stream at the evaporator coil. In dry climates, the latent cooling capacity is typically 10-15% of the total cooling capacity. If supply airflow is low, the evaporator coil will be colder, and the latent cooling capacity will be higher.

Liquid Line
Copper tubing which transports liquid refrigerant from the condenser to the expansion valve. In a split system it is the smaller, uninsulated pipe.

Manometer
A device used to measure pressures or differential pressures. It is used with duct pressurization devices and some airflow measurement systems. Digital meters are becoming standard practice. Measurements are commonly in Pascals (Pa) and Inches of Water Column (IWC).

Non-condensables
Unintended gas, typically water vapor or nitrogen that contaminates the HVAC system and adversely affects system performance. It can only be removed by evacuating the refrigerant system and then applying a deep vacuum.

Pa
Pascals, the metric system measurement of pressure where 25 Pa equals 0.1 IWC.

Package Unit
A package unit or RTU (rooftop unit) has all the HVAC electrical, mechanical and heat exchange components in a single "box" commonly located on the roof. Down flow for horizontal configurations are often possible using the same box. Package units are common in small and medium sized commercial buildings up to three stories. They are also used in residential application depending on accepted practice in specific geographic locations.

Quality Maintenance (QM)
Maintenance of HVAC equipment performed so that it meets either ACCA Standard 4 Residential Quality Maintenance or ACCA/ASHRAE Standard 180 Commercial Quality Maintenance.

Quality Installation (QI)
Installation of HVAC equipment that meets ACCA Standard 5 and is verified using ACCA Standard 9.

Receiver-Dryer
A cylindrical component brazed into the suction refrigerant line that stores liquid refrigerant letting only vapor pass thereby protecting the compressor for "slugging". Some include a

desiccant (and an indicator) to remove moisture which may have been introduced into the system. More common on refrigeration systems for food preservation.

Refrigerant
The working fluid which is pumped through the vapor compression system. Different refrigerants have varying thermodynamic properties, operating pressures, and efficiency characteristics. As of 2010 OEMs have generally switched to R-410a from R-22. The Dupont trade name Freon is commonly used.

Return Air
The airstream that is forced through the evaporator coil by the supply fan. In residential systems, the return air is mostly indoor air (some return duct leakage, and in some case some outdoor ventilation air). In commercial package units, the return air often includes a fraction of outdoor ventilation air set to maintain IAQ.

RTU
Abbreviation for "rooftop unit". Package system type common to commercial buildings. Ground mounting can occur and the unit still be called an RTU.

SEER
Seasonal Energy Efficiency Ratio is a performance metric defined by ARI 210/240 Standard to approximate seasonal operating efficiency of single phase, residential unitary air-cooled air conditioners with cooling capacities of less than 65,000 Btu/hour. SEER is the industry accepted metric for marketing residential air conditioners. As of 2006 USDOE required all systems have SEER ratings of 13 or higher.

Sensible Cooling Capacity
Represents the energy extracted by the vapor compression cooling system as represented by the temperature drop and the mass flow rate of air across the evaporator coil. In dry climates, the sensible cooling capacity is typically 85-90% of the total cooling capacity. In most residential dry climate applications, higher sensible cooling is desirous since indoor humidity levels are generally low.

Single- and Multi-Staged Compressors
Most residential systems utilize single stage compressors that vary in capacity from 1.5 to 5 tons. Some higher efficiency units utilize two-stage compressors, which allow the system to operate at a lower capacity level (and higher efficiency) if the thermostat can be satisfied. RTUs over 10 tons often have multiple compressors or a two-stage compressors. Digital variable capacity compressors are common in ductless mini-splits and are being introduced into central ducted systems.

Split System
The predominant residential air conditioning system found in single family homes. Unlike the package unit, the split system separates the indoor components (supply fan, evaporator coil, expansion valve) from the outdoor condensing unit (condensing coil and condenser fan). A field

installed set of liquid and suction refrigerant lines and control wires connect the condenser to the evaporator and air handler (usually a furnace).

Static Pressure
Represents the non-dynamic pressure within the HVAC system including the duct system. Pressure differentials relative to atmospheric pressure are highest directly upstream and downstream of the supply fan. The static pressure is the driving force for duct leakage.

Subcooling
The amount of temperature depression, expressed in °F, of liquid refrigerant (exiting the condenser) below the condensing temperature. Key measurement parameter in current RCA programs when a TXV is used.

Suction Line
Copper tubing used to carry refrigerant gas from the evaporator to the compressor. It is the larger diameter of the two refrigerant lines and must be insulated to minimize heat gain from surrounding air.

Superheat
The amount of temperature elevation, expressed in °F, of the refrigerant gas (exiting the evaporator) above the evaporation temperature. Key measurement parameter in current RCA programs when a fixed orifice is used.

Supply Air
Air leaving the evaporator coil and entering the duct system.

Temperature Split
A standard technician measurement for assessing the match of system airflow to system refrigerant mass flow. The "temperature split" between the supply and return air temperature multiplied by 1.08 times the nominal system airflow (= tonnage times 400 cfm/ton) has historically provided the technician with a rough estimate of sensible cooling capacity.

Tons of Air Conditioning
A common short hand designation of the total AHRI rated cooling capacity calculated by dividing the capacity in Btuh by 12,000 Btuh. The 12,000 Btuh number is the hourly cooling provided by 2000 pounds of ice melting over a 24 hour period.

Total Cooling Capacity
The sum of the sensible and latent cooling capacity calculated from the measurement of airflow, return dry bulb, inlet wet bulb, supply dry bulb, and supply wet bulb. The dry and wet bulb temperatures are used for the calculation of the reduction in enthalpy caused by the removal of heat and moisture (as liquid condensate) by the evaporator coil.

TXV- Thermostatic Expansion Valve
A thermostatic expansion valve has a diaphragm actuated plunger that when raised and lowered opens and closes the valve. The diaphragm is driven by a gas filled tube with a bulb at the other

end. The bulb is attached to the discharge or suction line as it leaves the evaporator coil. Often call a constant superheat valve it controls refrigerant flow to maintain a specified amount of superheat at the evaporator exit. TXV is better equipped to handle changes in conditions and refrigerant charge than a fixed orifice valve. Requires proper installation and insulation of temperature sensing bulb on the suction line leaving the evaporator coil.

Vapor Compression Cycle
A thermodynamic cycle where a working fluid (refrigerant) is compressed, condensed, expanded, and evaporator. The four key components are the compressor, two heat exchangers (high pressure condenser, low pressure evaporator), and a throttling device (expansion valve).