 # Final Report on the Expert Meeting for DIAGNOSTIC AND PERFORMANCE FEEDBACK FOR RESIDENTIAL SPACE CONDITIONING SYSTEM EQUIPMENT

Building Science Corporation Industry Team

15 July 2010

Work Performed Under Funding Opportunity Number:
DE-FC26-08NT00601

Submitted By:
Building Science Corporation
30 Forest Street
Somerville, MA 02143

Principal Investigators:
Joseph W. Lstiburek, Ph.D., P.Eng. ASHRAE Fellow
Betsy Pettit, FAIA

Phone Number: 978-589-5100
Fax Number: 978-589-5103
E-Mail: joe@buildingscience.com
E-Mail: betsy@buildingscience.com

Submitted To:
U. S. Department of Energy
National Energy Technology Laboratory
PM: Rob Martinez
E-Mail: Rob.Martinez@NETL.DOE.GOV

EXECUTIVE SUMMARY

1. Title: Final Report on the Expert Meeting for Diagnostic and Performance Feedback for Residential Space Conditioning System Equipment (Gate 1A)

2. Overview: The Building Science Consortium held an Expert Meeting on Diagnostic and Performance Feedback for Residential Space Conditioning System Equipment on 26 April 2010 on the NIST campus in Gaithersburg, Maryland. Featured speakers included Vance Payne of NIST, Haorong Li of the University of Nebraska, William Healy of NIST, Amr Gado of Emerson Climate Technologies, and Roy Crawford of Ingersoll Rand.

3. Key Results: Key results from this meeting were:

    a. Greater understanding of the sensors and controls currently incorporated into HVAC equipment.
    b. Greater understanding of the problems which reduce HVAC efficiency, and the sensors needed to detect these problems.
    c. Improved communication between HVAC manufacturers and regulating agencies about the possibility of mandating fault detection and diagnostics (FDD)

4. Gate Status: This project meets the "must meet" and "should meet" criteria for Gate 1A. The project provides source energy and whole building performance benefits by bringing field performance of heating and cooling equipment closer to rated performance. Especially for refrigerant based systems, the installed performance of space conditioning systems can benefit from improved installation procedures and training. Space conditioning systems with built-in sensors and diagnostics will also be easier to install correctly. The per-unit added cost of fault diagnostics is small relative to the average energy savings to be captured. Heat pump Fault Detection and Diagnostics (FDD) has the potential to reduce warranty costs, reduce installation callbacks, reduce peak load, improve comfort, and reduce electrical bills. Benefits therefore accrue to the manufacturer, the installer, the local utility, and the building occupant. Marketability depends on designing and marketing heat pump FDD in a way attractive to all of these parties. The key barriers to selling FDD are technician and owner expectations, which do not currently include this level of automation and interaction from HVAC systems.

5. Conclusions: Extensive information was presented on HVAC diagnostic sensor systems and their capabilities, yet, the general view was that, while still important, detecting loss of efficiency over time is not as high a priority as simply ensuring the correct installation of refrigerant-based equipment. However, HVAC sensors (such as temperature, pressure, power, and motors as sensors) definitely can have an important role for ensuring correct installations. Specifically the largest improvements in real system efficiency could be gained from diagnosing overly restrictive air distribution systems and improper refrigerant charge. The former can be identified using ICM fans as de facto sensors. The latter requires additional temperature or pressure sensors to be included.

    Next steps include developing a set of standard fault codes, developing standard language to communicate these faults clearly to homeowners, and including sensing and diagnostic requirements in code language. The fault codes should be developed by manufacturers together with existing standards organizations. DOE or the ICC could mandate onboard diagnostics, or Energy Star could add it as a requirement for certification. Expected benefits include energy savings, verification of rated performance, fewer callbacks, and reduced cost of warranty and service.

INTRODUCTION

The Building Science Consortium held an Expert Meeting on Diagnostic and Performance Feedback for Residential Space Conditioning System Equipment on 26 April 2010 on the NIST campus in Gaithersburg, Maryland. There were 36 in attendance. Invited speakers gave presentations in their particular area of expertise. The presentations were followed by discussion with the expert audience.

Figure 1: Audience at Expert Meeting

Figure 2: Vance Payne delivering a presentation

A summary of the individual presentations and major discussion points is provided in the sections below.

The final agenda for the meeting is listed in Appendix A. A list of attendees for the meeting is given in Appendix B. The presentations are included in Appendices C through G.

PRESENTATIONS

Speaker 1: W. Vance Payne, NIST

Presenter bio: Dr. Vance Payne's research activities have always centered around heat pumps and air conditioners. Recently, his work has focused upon fault detection and diagnostics in residential air conditioning and heat pump systems. The goal has been to develop methods of monitoring residential systems for faults that occur during the initial installation and throughout the life of the equipment all for the purpose of providing home owners with uninterrupted service from their vapor compression systems.

Presentation Title: *FDD Applied to a Residential Split System Heat Pump*

Presentation Summary:

Dr. Payne presented his research on automated fault detection in residential heat pumps. The system he has developed can identify several types of mechanical failure or blockage using a small number of inexpensive temperature sensors installed on the unit.

The fault detection and diagnostics (FDD) system uses an empirical equation to predict the relationship among temperatures. This correlation is determined in such a way that it is reliable whenever the equipment is operating at steady state. Deviation of the measured temperatures from the predicted values suggests a fault. The fault detection algorithm assigns a probability to a given fault based on the magnitude of the deviation. Fault probabilities above a certain threshold can be reported to the building owner or occupant.

The accuracy of FDD is critically dependent on accurate measurement of the benchmark which is the tested no-fault condition for that equipment. Therefore, optimum installed performance at testing is critical to FDD accuracy.

Dr. Payne made the following key points during his presentation:

- Independent variables for the fault-free performance equation are outdoor dry bulb temperature, indoor dry bulb, and indoor dew point.
- After comparing various equation forms for the performance equation, second order polynomials were found to be sufficiently accurate and easiest to implement. Although a general second order polynominal equation in three variables has 10 coefficients, 5 to 6 were found to be sufficient.
- Other quantities of interest can be calculated from measured temperatures: evaporator superheat, condenser subcooling, evaporator ΔT, and condenser air temperature rise.
- These quantities are correlated with faults. A moderate difference between the calculated fault-free value and the measured value likely indicates a fault. A table describes the signature of each fault in terms of which quantities are higher, lower, or similar compared to normal operation.
- It is necessary to compromise between quantity of data and equipment cost.
- Some manufacturers already have fault detection on board.
- FDD needs to be high confidence, to justify the cost of a repair visit. It also needs to be sensitive, to identify failure before thermal discomfort sets in. It is not clear where the threshold should be: for instance, 50% vs. 99%.
- FDD can help assure correct refrigerant charge, especially in heating mode, where current methods provide little guidance.
- It would be beneficial to have standardized fault codes for residential systems. This requires both uniform definitions of fault types, and a standard digital representation.
- It would be beneficial to develop fault detection rules for variable-speed systems and systems with outdoor and indoor units from different manufacturers.
- It would be beneficial to develop a method for comparing FDD algorithms or devices.
- It would be beneficial to develop FDD devices which learn in place. Each system has differences, and the FDD device is in a position to develop performance correlations specific to the installation.

<u>Comments, questions, and answers were as follows:</u>

- Q: Does each equipment model need to be tested in lab to generate a performance map?

A: Unknown. The current approach is to test each system, but it may turn out that systems are similar enough to permit general polynomials. Manufacturers already have this data.

- Q: Does this work at part load conditions?
  A: Yes, it works whenever the heat pump is operating at steady state: generally 5-6 minutes after it turns on.

Speaker 2: Haorong Li, University of Nebraska

Presenter bio: Dr. Haorong Li obtained his Ph.D. in Mechanical Engineering at Purdue University (2004) with an emphasis on automated fault detection and diagnostics for HVAC&R systems. He received his M.S. degree from Tsinghua University (2000, China) with an emphasis on automated control and simulation for thermal power plants, and his B.S. degree from Nanchang University (1997, China) with an emphasis on refrigeration and air conditioning engineering. Prior to his arrival at the University of Nebraska-Lincoln, he worked in Ray W. Herrick Laboratories as a research assistant and a post-doctorate research associate with Dr. Jim Braun.

Presentation Title: *Automated Diagnostics and Soft-Repair for Smart Homes*

Presentation Summary:

Dr. Li began by reiterating the scale of installation and maintenance shortcomings in current HVAC systems. Digital sensors and data processing have become inexpensive, and offer the chance to diagnose and correct problems at a fraction of the cost of system replacement or retrocomissioning. In the best case, adapting the control strategy to the system constraints can constitute a “soft-repair,” reducing the impact of malfunctioning equipment without the expense of a physical repair. In other cases, collecting and analyzing data over a longer period can reduce the technician hours required for accurately diagnosing failures.

The soft-repair system can take advantage of sensors which are already installed for normal HVAC operations, while adding analysis capabilities to extract more meaningful knowledge about the system. In the context of commercial buildings, information can be shared among similar buildings operated by the same entity. Comparisons with other local buildings, and with other sources of data such as local weather and manufacturer ratings, can help to isolate system performance from external influences.

Dr. Li made the following key points during his presentation:

- 90% of engineering takes place before the HVAC system is installed, but 75% of costs occur after.
- 71% of HVAC systems have some sort of performance problem, increasing energy use by 20% to 30% on average.
- Immediate repair is often not cost effective. More problems can be addressed at the time of scheduled service, or in a batch. Some problems cannot be cost effectively repaired, but their impact can be taken into account by the system controllers.
- Feedback can motivate and support changes in user behavior.

- Multiple inexpensive temperature sensors coupled to inexpensive microcontrollers can replace, or at least augment, fewer more expensive pressure sensors for effective fault detection and diagnostics in refrigerant-based systems.
- Automated FDD for HVAC has been researched for 20 years, but is little used. The reasons include long device lifecycle, lack of clear actions to take based on reported errors, and the need for a direct method for devices to notify occupants of malfunction. Of course, lack of adoption is self-perpetuating, as buyers look for proven field performance.

Speaker 3: William Healy, NIST

Presenter bio: Dr. William Healy joined the Heat Transfer and Alternative Energy Systems Group at NIST in March 1999 and assumed the duties of Group Leader in 2007. He manages the program entitled Measurement Science to Improve Building Energy Performance within the BFRL Strategic Goal of Net-Zero Energy, High Performance Buildings. His current research interests involve the development of metrics to assess the performance of wireless sensors in buildings, the optimization of energy monitoring systems to provide feedback on energy consumption, and the development of improved test methods for rating the performance of residential water heaters.

Presentation Title: *Building Sensors and Energy Modeling Systems*

Presentation Summary:

Dr. Healy presented an overview of currently available wireless digital communications for sensor networks, and areas where further technological advances are needed. These wireless sensors would in practice be integrated into a system which processes the measurements for display or automatic response.

Dr. Healy made the following key points during his presentation:

- Sensing capabilities in homes have lagged those of cars, due in part to building stock inertia and lack of centralized manufacture. The lack is not so much in number of sensors themselves, as in collecting and analyzing the data.
- Sensor needs include:
  - electric metering
  - fuel gas flow
  - water flow
  - ventilation air flow
  - occupancy
  - light including color
  - thermal comfort
  - Indoor air quality sensors are a major need, pending determination of what compounds to measure.
- The goals of easy and fast installation (without expert knowledge) point to wireless sensors as a good option. This increases hardware cost, but market share is still growing. People keep predicting much less expensive sensors, but market price is still around $70.

- For sensors, power consumption is the driving design concern, and is more important than latency or bandwidth. IEEE 802.15.4 is designed with this in mind, and is one likely candidate technology. EnOcean also has a proprietary protocol for low-power applications.
- Star networks are simple and use less power, but mesh networks may be more reliable in the noisy and heavily shielded radio environment of buildings.
- There is still little real world experience with the performance of sensor networks in real buildings. Microwave ovens and other 2.4 GHz radio devices cause interference. Brick walls and sheet metal are the worst signal shields (greatest signal attenuation).
- Plug and play sensor networks are still not available. IEEE 1451 is meant to help, by providing a standard data model and standards for self announcing and documenting sensors.
- In the longer term, sensor nodes should:
    - Automatically determine location (currently feasible outdoors)
    - Diagnose and report low battery and gross damage
    - Route around network damage
- Typical wireless sensors draw ~15 mW while transmitting or receiving, and only ~15 µW in sleep mode. By minimizing network use, batteries can last up to 5 years---close to their shelf life. Harvesting small amounts of energy from heat or vibrations is a next-generation technology.
- An alternative to sensor-intensive measurement is to use fewer sensors with more analysis. Many household appliances have distinctive signatures formed by the magnitudes of their real and reactive power draws. These signatures can be used to compute the energy used by each device from measurements at a single point.
- Monthly power consumption reporting in the form of a utility bill is not useful in driving conservation. Studies show savings between 5% and 20% of electrical consumption by providing continuous real time information.

<u>Comments, questions, and answers were as follows:</u>

- Comment: There is a new Bluetooth standard (Bluetooth low energy) designed to meet the constraints of battery-powered wireless sensors.

Speaker 4: Amr Gado, Emerson Climate Technologies

<u>Presenter bio:</u> Dr. Amr Gado obtained his Ph.D.in Mechanical Engineering from the University of Maryland, College Park in 2006 in the area of transient behavior of heat pumps. In his dissertation, he devised a method to allow the laboratory testing of a heat pump during transient operation independent of the conditioned space. Currently with the White-Rodgers Division of Emerson Climate Technologies, he started his career developing controls and new fault detection and diagnostics methods for the residential HVAC market.

<u>Presentation Title:</u> *HVAC Sensors, Controls, and Human Feedback Interfaces*

<u>Presentation Summary:</u>

A main focus of Dr. Gado’s presentation was using “compressors and fan motors as a sensor.” Important operational diagnostics can be performed on refrigerant systems using the compressor with two current transformers and a control board. Adding one pressure sensor dramatically improves the diagnostic capability. Fan motor sensing technology, integrated in the unit, can be used to verify airflow within ±15%. These sensors can indicate component or system failure, refrigerant over- or under-charge, and errors in system design. Taken together, these faults are responsible for important large losses of efficiency relative to equipment ratings.

Dr. Gado made the following key points during his presentation:

- Between 50% and 73% of HVAC systems have installation problems, leading to 30% to 50% reductions in efficiency. The most important of these problems include: inadequate airflow, improper refrigerant charge, mismatched systems, improperly sized systems, and duct leakage.
- Many of these problems can be corrected without replacing the equipment:
  - clean filter
  - defrost
  - line set insulation
  - compressor failure
  - refrigerant charge
- Refrigerant changing should involve measuring pressure, subcooling, and superheat, but this is rarely done. An automated system to guide proper refrigerant charge would save technician time and improve performance. Such a system would require a pressure transducer in addition to the existing compressor-as-a-sensor technology.
- Adding onboard diagnostics provides multiple benefits. The homeowner receives more information about system faults. The technician is more informed about system status. After service, the diagnostics verify for the homeowner that the technician has corrected the problem.
- The feedback systems in compressors and variable speed brushless DC motors already incorporate various sensors. Using these as sensors makes 9 fault codes available. If communicating thermostat and more sensors are added, there can be over 40 fault detection and diagnostic codes.

<u>Comments, questions, and answers were as follows:</u>

- Q: Does displaying a fault in "plain English" on the thermostat conflict with the desire to have standard fault codes?
  A: There can be standard faults, and optional additional text faults implemented by manufacturers.
- Q: Can equipment automatically call back to the manufacture or maintenance firm, over WiFi, TCP/IP
  A: This is possible, but not all homeowners are tech savvy. Many may not want appliances bypassing their control.
- Comment: EPA's new Energy Star specification for climate controls will require that any protocols used between thermostat and AMI (advanced metering infrastructure) equipment or computer networks are open standards.
- Q: How expensive are current transducers?
  A: Depends on the manufacturer. Prices are about an order of magnitude more than temperature sensors, but much less than pressure sensors ($1-$3). The existing Emerson system doesn't use a current transducer, it just reports a threshold current or no current.
- Q: What about reporting when the air distribution system is too restrictive?

A: This could be something like the California Energy Commission Title 24 fan power per CFM requirements. If it's part of the AHU, a finger pointing exercise can result: although the HVAC installer or designer is actually at fault, the equipment might be blamed.

- Q: How does the ECM motor measure airflow?
  A: RPM is measured using back-EMF, and then torque and airflow are calculated based on empirical curves for each motor design.
- Q: What would it take to output airflow CFM, which is already known internally?
  A: Some of the latest Lennox products display CFM on the thermostat.
- Comment: Looking at power consumption is not enough. Some failures manifest as reduction of heating or cooling output, with reduction of electrical consumption as a side effect. Looking at capacity reduction is at least as important to recognize efficiency losses.

Speaker 5: Roy Crawford, Ingersoll Rand

<u>Presenter bio:</u> Dr. Roy Crawford received his B.S. and M.S. degrees from the University of Illinois—Urbana and his Ph.D. from Iowa State University, all in Mechanical Engineering. He is currently the Director of Advanced Technology, Residential Systems, for Trane, a business of Ingersoll Rand in Tyler, Texas. He leads the development and application of new technology in residential air conditioners, heat pumps, furnaces, and other environmental control equipment. Previously, he held various research & development leadership roles at Honeywell International in Minneapolis, Minnesota and Carrier Corporation in Syracuse, New York. He also was an Assistant Professor of Mechanical Engineering at the University of Illinois—Urbana where he also co-founded the Air Conditioning & Refrigeration Center.

<u>Presentation Title:</u> *HVAC Equipment Manufacturer's Perspective*

<u>Presentation Summary:</u>

Dr. Crawford's presentation addressed the constraints which have deterred wider deployment of sensors and automated diagnostics to date. Manufacturers aim for 99% reliability in the first year and 95% reliability over a 15 year lifetime. Building electronics which improve on this reliability record is hard to accomplish, and electronics failures which keep the system from working make for dissatisfied customers. Homeowners, installers, manufacturers, researchers, and regulators each value different properties of the HVAC equipment. The existing products represent a compromise between these many needs.

Ultimately, someone has to pay for the added sensors and logic. Pressure sensors, which would be the most directly useful, are still expensive, although prices have been falling. Further price reductions would lead to inclusion in more models, as would incentives or requirements for onboard diagnostics.

Dr. Crawford made the following key points during his presentation:

- Most HVAC problems are due to errors during installation:
  - Airflow mismatched to ductwork

    - Duct leakage
    - Ductwork design
    - Refrigerant charge
- Operational issues include refrigerant leakage and inadequate filter maintenance, but these have less influence. Based on their empirical testing, outdoor coil fouling only becomes a significant penalty in extreme circumstances.
- Digital diagnostics can be less reliable than the existing system, thereby increasing faults rather than decreasing them. Electronics sensitivity to vibration, moisture, temperature, and electrical disturbance are often factors affecting reliability to be addressed.
- Refrigerant charging is one area where onboard sensors and algorithms could make a big difference. Charging by weight is accurate, but too difficult when servicing an existing system. Most new systems have TXV or EXV, and current charging procedure only works above 65°F outdoor temperature. The Trane XL20 has automated charge diagnostics using temperature and pressure sensors to measure subcooling, and a restricted charge port. Installer response has been mixed.
- Every connection to the refrigerant lines is a potential leak. Schrader valves are particularly risky. This favors sensors which do not need replacement or removal over the lifetime of the equipment.
- Indoor airflow can be measured, and can help verify correct motor tap or DIP switch selection. Proper flow rate depends on indoor/outdoor coil matching and required dehumidification.
- Static air pressure measurement can reveal mismatch between ductwork and AHU. The challenge is that "HVAC installers don't want to be told that their ductwork is bad."
- Refrigerant pressure measurement is more useful than temperature. Pressure can be estimated with temperature sensors, but this is location sensitive and only works when the system is running at steady state. Therefore, referring to Figure 3, pressure and temperature measurement at state point 3 (condenser outlet or expansion device inlet) is recommended. Additional pressure and temperature measurement at point 1 (compressor inlet) would be the next step to further improve performance tracking and fault detection.
- Airflow is hard to measure directly, especially as velocity varies across the duct. Static pressure is much easier and more uniform.
- Air temperature and relative humidity are hard to measure because they vary over the coil area.
- Operational diagnostics require permanent equipment. This adds complexity for the homeowner, and additional points of failure. Diagnostics at time of installation are the responsibility of the technician, who can use the same equipment on many installations.
- The homeowner does not want to be cut out of the loop by equipment that automatically contacts a third party.
- Efficiency measurements over time are difficult to do accurately and reliably. There are a huge number of combinations of indoor and outdoor unit. Flow rate measurement, whether of air or of refrigerant, is difficult, and therefore expensive.
- Homeowners are unlikely to pay for onboard diagnostics. Technicians might if they are convinced it will save them time and service problems. Manufacturers might if it reduced warranty costs. Utilities and government are the most directly concerned with efficiency, and therefore the most likely to support these systems.

<u>Comments, questions, and answers were as follows:</u>

- Q: What has been your experience on reliability and accuracy of pressure sensors?
- A: Good so far, but there is limited experience.

- Q: Will onboard diagnostics save energy?
- A: Some will, such as low airflow or wrong refrigerant charge. Have not seen any good field data quantifying this. It is a good research question.
- Q: What about duct sealing?
- A: Duct sealing is low hanging fruit, and should be done first.
- Q: What are your thoughts on cooperating more with governments and utilities?
  A: Manufacturers already are. California Title 24 now requires charge verification and airflow verification. Somebody gets paid to do it, and it costs around $400 per house. The marketplace has created an incentive to do it better (less expensively). It may be possible to have on board diagnostics accepted as an alternate verification method, which gives a relative maximum price point that the market might bear.
- Q: What is the markup between manufacture and sale?
  A: Everyone takes a markup: manufacturer, distributer, wholesaler, and installer. "It adds up to a lot."
- Comment: We need to determine whether the addition of these sensors will save energy, and then we can start discussing who pays for it, and how we're implementing it. There are shockingly bad installations in the field. But if it was installed correctly, we might not be saving anything, or even having worse problems because of complexity of sensors. It's a question of cost-benefit.
- Comment: a lot of these failures manifest clearly as can't cool/house warms up, and is clear to the homeowner. What are not obvious are things like fouling of heat exchangers, or loss of refrigerant charge—but if you had no leaks from the beginning, you shouldn't have leak problems. If your filter is set up correctly, fouling is less of an issue. There might be less on the table than we think there is. The biggest bang for buck is in correct installation—there are many systems that have been kludged together many times as a fix to a fix. This is more important than monitoring efficiency degradation over time.
- Comment: Equipment is reliable and efficient, so there is little opportunity to save energy through controls. But providing feedback to the homeowner can change behavior, and save energy that way.
- Comment: Aside from energy efficiency, can these diagnostics provide quality assurance, and verify that we are delivering on the promise that we have been stating? This is a system design/installation/commissioning issue more than anything else.
- Comment: One other opportunity that hasn't been mentioned is detecting when equipment is close to failure. With forewarning and time to shop, the homeowner could consider higher efficiency equipment, as opposed to whatever is available on short notice from an installer.

General Discussion around Key Questions

Excessive resistance to airflow is a serious problem in reducing system efficiency. The AHU is rated for external static pressure (ESP) by the manufacturer (usually 0.5 inch water column or 125 Pascal), but it is often difficult to measure the true ESP in real systems, because it often involves drilling pressure tap access holes close to add-on refrigerant coils. Because of that, static pressure differential is usually measured in the ducts, from return to supply, rather than across the air handler, inboard of add-on coils, filter housings, etc. That does give an indication of the duct system resistance to airflow, but it does not show the total resistance that the AHU is working against. California Title 24 provides a model for measuring both airflow and power, but not external static pressure. That test significantly increases the cost of compliance. With common ICM fans, it should be easy to report airflow and power draw to easily detect systems with excessive resistance to airflow. AHU manufacturers may be able to provide that information at a much lower cost than currently required by raters to make measurements.

Charge verification is the next target, and can be done at installation. Once the sensors have been installed, it should be possible to monitor over time in ways that do not reduce reliability. Referring to Figure 3, Trane equipment measures liquid temperature and pressure at point 3 in the vapor compression cycle (high side coil outlet), plus indoor and outdoor temperature. This allows proper charging during the cooling season. During the heating season, the technician can only guess, and come back when the outdoor temperature is above 65°F.

Although not usually done, superheat measurement at point 2 (compressor outlet) on Figure 3 has been shown to provide a good indicator of charge in heating if the system has been well characterized by the manufacturer over a range of operating conditions. Overcharging is common and less detrimental for cooling operation than for heating. Heating COP falls off sharply with overcharging. Manufacturers would like to add the tools necessary to evaluate refrigerant charge during the heating season, but do not see the cost being supported by the current market. Anything that helps a manufacturer assure better installations and reduce warranty and service cost is desirable, but the benefit must be balanced against the cost to achieve that.

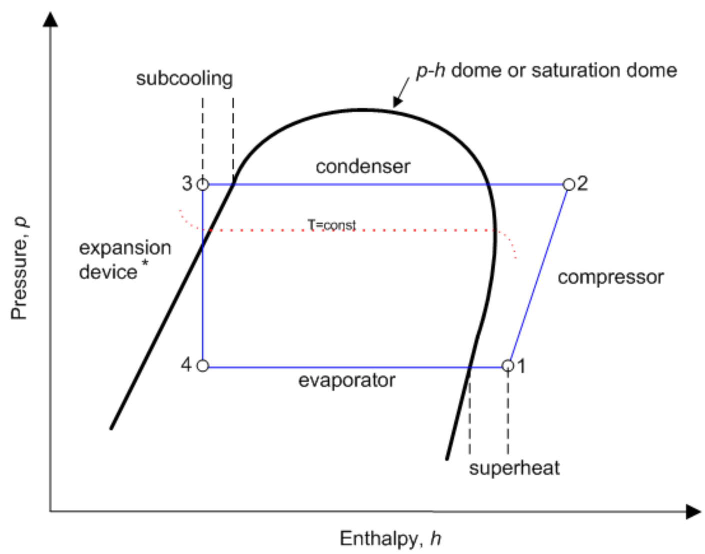

Figure 3: Vapor Compression Cycle

Recommended system charge is a compromise between heating and cooling efficiency. It also depends on indoor and outdoor conditions, and indoor and outdoor coil matching. Ideally, refrigerant charge would change between heating and cooling seasons, or even better, between shorter periods of alternately heating and cooling. Twice-yearly service to adjust charge between heating and cooling seasons is out of the question; and the costs versus benefits for adding equipment (such as a refrigerant charge compensator tank or receiver, and electronic expansion valves) to optimize both summer and winter charge have not yet been fully determined.

Diagnostics could be added to all models across the board, or just at the high-end. The high end has larger profit margins, and those systems already have more sensors. Building America already requires high efficiency systems, so these are the systems that matter for reaching BA performance targets. Higher end equipment is less tolerant of variation in charge–small variations lead to significant changes in performance–and high efficiency systems with large coils show little variation in subcooling as charge is added, making precise charging more difficult. The manufacturing representatives would prefer to design systems that will be used everywhere, not just in the 5% of premium systems. Engineering effort to add diagnostics might focus on the systems allowed under the new DOE rulemaking which is expected to raise the minimum SEER and HSPF. The proposed new levels will be published in the Fall of 2010 with the final rule published in mid 2011. Implementation dates have not yet been determined but are expected to be sometime between 2013 and 2016. Changes in the Energy Star specification for residential heat pumps and central AC could be increased sometime following the publication of the final rule.

If the DOE requires better dehumidification performance, nominal SEER ratings will drop, but EER under real conditions should stay about the same. It would be useful to test equipment at more points (in addition to, or in place of tests such as SEER), to provide needed information about dehumidification to designers, modelers, and raters.

Communication to the homeowner should include not just a red "check engine" light, but also an estimate of the long-term financial impact. Occupants are more likely to take action if they know a fault is costing them $100+ per month. For occupants, it is most helpful to announce faults at the thermostat. For ensuring correct installation, another diagnostic display close to where the technician is working (usually at the outdoor unit) would be useful.

It would be useful to have a consistent set of fault codes across the industry. The BACnet and ClimateTalk protocols should be evaluated for applicability. Three manufacturers already have their own proprietary protocols, and because of that investment may be reluctant to adopt different ones or participate in developing a standard. Still, it may be possible to develop a standard among Building America partners, and see if it gains wider traction within industry. There was a general feeling among the meeting participants that DOE/EPA and utility leadership in this area would be positive.

Appendix A: Expert Meeting Plan/Agenda

WWW.BUILDINGAMERICA.GOV

Building America Expert Meeting Agenda

Diagnostic Measurement and Performance Feedback for Residential Space Conditioning Equipment

Date/Time:	**Monday, 26 April 2010** **9:00 am to 3 pm**
Location:	NIST, Gaithersburg, MD (www.nist.gov) Building 101, Employee's Lounge (Portrait Room)
Meeting Manager:	Armin Rudd, Building Science Corp. (www.buildingscience.com)

Featured Speakers:

- Fault Detection and Diagnostics for Space Conditioning Equipment (Vance Payne-NIST and Haorong Li-U of Nebraska)
- Sensors and measurement research (William Healy-NIST)
- HVAC sensors, controls, and human feedback interfaces (Amr Gado-Emerson)
- HVAC equipment manufacturer's perspective (Roy Crawford-Trane)

The objective of this session is to explore the development needs and commercial possibilities for improved start-up commissioning and long-term operating performance of residential HVAC systems through measurement and feedback systems. The eventual goal is to provide HVAC equipment installers and high-performance home occupants with easily observable means to determine when and why the equipment is not operating properly and efficiently. This is important to ensure the persistence of energy savings toward the Building America target of broad energy retrofits of existing homes and development of high performance new homes to reduce residential carbon emissions 20% by 2020 and 80% by 2050.

Key questions regarding this meeting:

1. What measurements are needed to determine whether or not space conditioning equipment is operating properly and efficiently? What accuracy is required for each measurement?

2. Relatively low-cost sensors such as those to protect against over/under voltage and over/under pressure are currently in common use as standard or optional equipment. Is it possible to utilize these types of sensors in an expanded feedback system? What are present manufacturer assumptions about these sensors' long-term durability and performance?

3. Ideally, measuring the delivered heating, cooling, or dehumidification capacity relative to the energy consumed would allow real-time determination of the equipment operating efficiency. The temperature, humidity, pressure, flow, and power sensors needed to determine a specific efficiency target would be unacceptably expensive. Is it possible to utilize or develop low-cost, durable sensors that would allow a meaningful determination that the equipment was operating within an acceptable tolerance range rather than at a specific efficiency target?

4. What level of feedback display would be needed to make the performance monitoring system effective?

Would a simple red light/green light system at the equipment be adequate to provide ample notice of good/bad performance, or would a more complex digital type display, perhaps integrated into a thermostat, be needed to be effective?

5. What increase in cost would the market likely bear for this added performance monitoring information, and what would be needed to meet that cost target?

Invitees:

Participants will be key people working in the fields of: residential HVAC space conditioning, sensor and measurement technology, microprocessor-based human interfaces, residential construction, and building energy efficiency.

Meeting Agenda:

- 9 am Welcome and Meeting Introduction
- Brief Building America Program Overview
- 9:15 to 12:15 Presentations with Q&A time (45 minutes each presenter)
- 12:15 to 1:00 Lunch break (lunches provided)
- 1:00 to 1:45 Presentation with Q&A
- Group discussion to cover key questions
- Wrap up, action items, and follow-up plan
- 3 pm Adjourn meeting

Presenter Bios

Dr. Vance Payne's research activities have always centered around heat pumps and air conditioners. Recently, his work has focused upon fault detection and diagnostics in residential air conditioning and heat pump systems. The goal has been to develop methods of monitoring residential systems for faults that occur during the initial installation and throughout the life of the equipment all for the purpose of providing home owners with uninterrupted service from their vapor compression systems.

Dr. Payne has worked on an alternative rating method for mixed system air-conditioners or heat pumps operating in the cooling mode. This method is intended to provide accurate rating results for systems consisting of indoor and outdoor components that are not normally tested together during the rating process. The new method seeks to reduce testing requirements while providing accurate rating methods for these mixed systems. In a related effort, he surveyed the cooling mode and heating mode efficiency and capacity ratings of mixed systems listed in the ARI directory and pointed out trends for use by DOE in their rulemaking deliberations.
http://www2.bfrl.nist.gov/profiles/profiles.asp?lastname=payne

----

Dr. Haorong Li obtained his Ph.D. in Mechanical Engineering at Purdue University (2004) with an emphasis on automated fault detection and diagnostics for HVAC&R systems. He received his M.S. degree from Tsinghua University (2000, China) with an emphasis on automated control and simulation for thermal power plants, and his B.S. degree from Nanchang University (1997, China) with an emphasis on refrigeration and air conditioning engineering. Prior to his arrival at the University of Nebraska-Lincoln, he worked in Ray W. Herrick Laboratories as a research assistant and a post-doctorate research associate with Dr. Jim Braun on several State and Federal funded research projects with an overall funding of nearly $2 million. His primary research interests are in the modeling, analysis, control, and diagnostics of thermal systems, which involve the design of physical and empirical models, automatic control algorithms, and automated fault detection and diagnosis systems for HVAC&R systems and thermal power plants. He has been actively involved with the American Society of Heating, Ventilating and Air-Conditioning Engineers (ASHRAE) and received the Willis Carrier/ASHRAE Fellowship and ASHRAE Grant-in-aid. The team he led won the 4th place of the 18th Annual Burton D. Morgan Entrepreneurial Competition (Gold Division) for moving the technology resulting from his research toward commercialization.

Dr. William Healy joined the Heat Transfer and Alternative Energy Systems Group at NIST in March 1999 and assumed the duties of Group Leader in 2007. He manages the program entitled Measurement Science to Improve Building Energy Performance within the BFRL Strategic Goal of Net-Zero Energy, High Performance Buildings. His current research interests involve the development of metrics to assess the performance of wireless sensors in buildings, the optimization of energy monitoring systems to provide feedback on energy consumption, and the development of improved test methods for rating the performance of residential water heaters. Dr. Healy has also investigated improved sensing methods for determining the moisture content

within building envelopes. As a result of this effort, he and his collaborators were awarded a patent on the use of ultra-wideband radar to map the moisture state of a wall. Additional efforts have included support of the guarded hot plate development through finite element modeling and participation in efforts by the Department of Homeland Security to develop the infrastructure to allow for data from sensors to be propagated to applications that require knowledge of hazard levels. Dr. Healy is a member of the American Society of Mechanical Engineers (ASME) and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). He currently serves as the chair of the Wireless Applications Subcommittee in ASHRAE TC 7.5: Smart Building Systems and as a voting member for ASHRAE Standard Project Committee 118.2: Method of Test for Rating Residential Water Heaters. He has previously served as a voting member on ASHRAE TC 4.4: Building Materials and Building Envelope Performance. He is also an instructor in the Johns Hopkins University Engineering for Professionals program, where he teaches courses in Applied Heat Transfer and Thermal Systems.
http://www2.bfrl.nist.gov/profiles/profiles.asp?lastname=healy

----

Dr. Amr Gado obtained his Ph.D.in Mechanical Engineering from the University of Maryland, College Park in 2006 in the area of transient behavior of heat pumps. In his dissertation, he devised a method to allow the laboratory testing of a heat pump during transient operation independent of the conditioned space. Currently with the White-Rodgers Division of Emerson Climate Technologies, he started his career developing controls and new fault detection and diagnostics methods for the residential HVAC market. After completing an MBA in 2009 and being awarded, with his team, the 3rd place in the Society of Advancement of Management National Business Plan Competition, Dr. Gado is now focusing his efforts with Emerson on developing new business models to commercialize technologies as well as managing the Advanced Technologies Laboratory. He is a member of ASHRAE and the IIR.

Dr. Roy Crawford is currently the Director of Advanced Technology, Residential Systems, for Trane, a business of Ingersoll Rand in Tyler, Texas. He leads the development and application of new technology in residential air conditioners, heat pumps, furnaces, and other environmental control equipment. Previously, he held various research & development leadership roles at Honeywell International in Minneapolis, Minnesota and Carrier Corporation in Syracuse, New York. He also was an Assistant Professor of Mechanical Engineering at the University of Illinois—Urbana where he also co-founded the Air Conditioning & Refrigeration Center.

Crawford has been an active member of the American Society of Heating, Refrigerating, & Air Conditioning Engineers (ASHRAE) for over 25 years where he has served on numerous technical and standards committees. He has published over 30 research papers in various air conditioning and refrigeration journals. He received his B.S. and M.S. degrees from the University of Illinois—Urbana and his Ph.D. from Iowa State University, all in Mechanical Engineering.

Appendix B: Expert Meeting Attendee List (based on sign-in sheet)

Last Name	First Name	Company
Bergey	Daniel	Building Science Corporation
Bloemer	John	Research Products Corp/Aprilaire
Bushby	Steve	National Institute of Standards & Technology (NIST)
Christensen	Dane	National Renewable Energy Laboratory (NREL)
Crawford	Roy	Trane Residential Systems/Ingersoll Rand
Daken	Abigail	U.S. Environmental Protection Agency (USEPA)
Davis	Wesley	Air Conditioning Contractors of America (ACCA)
Domanski	Piotr	National Institute of Standards & Technology (NIST)
Donelon	Joann	Emerson Climate Technologies
Dougherty	Brian	National Institute of Standards & Technology (NIST)
Douglas	Jon	Lennox Industries
Fanney	Hunter	National Institute of Standards & Technology (NIST)
Fisher	Bethany	National Renewable Energy Laboratory (NREL)
Gado	Amr	Emerson Climate Technologies
Gehl	Tony	Oak Ridge National Laboratory (ORNL)
Guernsey	Matt	TIAX
Healy	Bill	National Institute of Standards & Technology (NIST)
Hunt	Dave	Pacific Northwest National Laboratory (PNNL)
Leopkey	Ted	Environmental Protection Agency (EPA)
Li	Haorong	College of Engineering University of Nebraska-Lincoln
Logee	Terry	U.S. Dept. of Energy (USDOE)
Lutz	Jim	Lawrence Berkeley National Laboratory
Luyo	Luis	National Institute of Standards & Technology (NIST)
Medepalli	Sarah	ICF International
Munk	Jeffrey	Oak Ridge National Laboratory (ORNL)
Olsen	Mark	Lennox Industries
Payne	Vance	National Institute of Standards & Technology (NIST)
Rudd	Armin	Building Science Corporation
Taylor	Sam	U.S. Dept. of Energy (USDOE)
Ueno	Kohta	Building Science Corporation
Ullah	Tania	National Institute of Standards & Technology (NIST)
Veronica	Dan	National Institute of Standards & Technology (NIST)
Wenqi	Guo	National Institute of Standards & Technology (NIST)
Wiggins	Matt	TIAX
Winkler	Jon	National Renewable Energy Laboratory (NREL)
Yashar	David	National Institute of Standards & Technology (NIST)