Arnold Schwarzenegger
Governor

RESIDENTIAL THERMOSTATS: COMFORT CONTROLS IN CALIFORNIA HOMES

PIER FINAL PROJECT REPORT

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Prepared By:
Lawrence Berkeley National Laboratory

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Prepared By:
Lawrence Berkeley National Laboratory
Project Manager: Alan Meier
Authors: Iain Walker and Alan Meier
Berkeley, CA 94720
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Public Interest Energy Research (PIER)
California Energy Commission

Kirsty Chew and Martha Brook
Contract Manager

Insert: Program Area Lead Name
Program Area Lead
Insert: Program Area Name

Insert: Office Manager Name
Office Manager
Insert: Office Name

Martha Krebs
PIER Director

Thom Kelly
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

Melissa Jones
Executive Director

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1.0 Executive Summary

This report summarizes results of a literature review, a workshop, and many meetings with demand response and thermostat researchers and implementers. The information obtained from these resources was used to identify key issues of thermostat performance from both energy savings and peak demand perspectives. A research plan was developed to address these issues and activities have already begun to pursue the research agenda.

The key issues identified were:

- Design and implementation of user interfaces tend to be poor in current thermostats
- The wide range of what occupants find comfortable presents a challenge to designing improved thermostats
- There is a considerable range of existing advanced thermostat controls whose effectiveness requires evaluation
- Other countries have more sophisticated controls that may be applicable in California
- Existing controls lack features that some users consider desirable and could also have significant energy savings
- Little is known about optimizing user interfaces for comfort controls

The key points of the research plan were:

1. Understand how people use and regard thermostats today
2. Improve the effectiveness of user interfaces
3. Develop standards and design specifications
4. Reconsider the role of the thermostat in the context of very low energy homes, zero-energy homes, and "healthy" homes
5. Investigate ways to link public information to more effective thermostat habits

Recommended future activities are:

- Follow-up with further research to address the five key points in the research plan.
- Ensure that all interested parties (manufacturer's, utilities, consumer groups, regulatory bodies (the Energy Commission, EPA and DOE)) work together to find solutions
- Collaboration with EPA in developing new EnergyStar specifications.
- Collaboration with other research entities (e.g., ASHRAE)

2.0 Literature Review

2.1. Introduction

The goal of this literature review is to improve our understanding of the factors affecting the effectiveness of the thermostat and its use including technical, behavioral, and organizational aspects. There is a vast quantity of literature available on thermostats in general. However, not all the work is relevant for this study. To this end, the literature review forsakes depth for focus. It also has a bias towards California issues including Demand response (DR), and applicability and relation to Title 24 (Building Efficiency Standards) and Title 20 (Appliance Standards).

The literature review begins with a look back on the history of thermostats and continues with sections on the technical aspects of performance, how thermostats are used, how people interface with them and concludes with a discussion of energy and demand response issues.

The results of the literature review were used to look to the future of thermostats and develop recommendations for future research that will allow us to capture the potential benefits of improved thermal and comfort controls.

A conference paper summarizing some the results of the literature review can be found in Appendix C.

An Historical Perspective

Although heating and cooling for thermal comfort in dwellings have been around since the first fire was lit in a cave, for most of history the control of thermal comfort required human intervention. The Romans were among the first to move on from the concept of a simple open fire to a central heating system. They utilized under-floor heating, where hot air from a wood fire flowed through under-floor chambers. Because the fire required constant attention to remove ashes, add fuel (wood in small pieces (typically less than 3 in. (75mm) diameter)[1]) and control the fire to maintain a suitable balance of air flow and temperature. Only the wealthiest could afford the staff (usually slaves) required to maintain the fire in a private residence.[2]

Cornelius van Drebbel (born in 1572 in Alkmaar, Holland) is commonly credited[3] with inventing automated temperature control in the form of an electromechanical device - what we would recognize as a thermostat. He used it to regulate the temperature of ovens and chicken incubators.

The reliance on cheap (or slave) labor to heat homes was still in evidence for most of the previous century, although there were some early adopters. One of whom was H.L. Mencken who wrote[4]: "… Of all the great inventions of modern times the one that has given me the most comfort and joy is one that is seldom heard of, to wit, the thermostat.". A key reason for his joy was that the War of 1914-1918 led to the furnacemen taking better paid jobs at the shipyards and he had to tend his own coal furnace - dirty, back-breaking work - and his house was never comfortable. Upon installation of a gas furnace controlled by a thermostat he had the following to say: "I began to feel like a man liberated from the death-house. I was never too hot or too cold. I had no coal to heave, no ashes to shift. My house became so clean I could wear a shirt for five days. I began to feel like work, and rapidly turned out a series of imperishable contributions to the national letters. My temper improved so vastly that my family began to suspect senile changes.". He clearly saw the thermostat as a device of liberation. In the same way as automatic washing machines, dishwashers, vacuum cleaners and refrigerators have removed much of the burden of household labor.

More modern history in the U.S. revolves around a couple of companies who are still in the business of building thermal controls today: Johnson and Honeywell.

In terms of regulating the temperature of buildings - particularly central heating and cooling systems we have to fast forward to 1883, when Warren S. Johnson (of Johnson Controls[5]) received a patent for the first electric room thermostat. Upon his death in 1911, Johnson Controls decided to focus on temperature controls for nonresidential buildings only.

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[1] http://www.romans-in-britain.org.uk/inv_central_heating.htm

[2] This technology is still used in Korean homes (called an *ondol*, though the fuel has evolved from wood to charcoal to district heating.

[3] www.tecsoc.org/pubs/history/2002/nov7.htm

[4] Mencken, H.L. 1931. *The Boons of Civilization* (from the American Mercury, January 1931, pp. 33-35).

[5] www.johnsoncontrols.com/publish/us/en/about/history.html

At almost the same time (1885) Albert Butz developed a furnace regulator that used a flap to control air entry (and thus heat output) to a furnace[6]. His company (the Electric Heat Regulator Co.) eventually became Honeywell.

Butz's 1885 Furnace regulator

In 1906 Honeywell produced the first automatic programmable setback thermostat. It used a clock to turn the temperature down at night and up in the morning.

First Programmable Thermostat

The first anticipator thermostat was produced in 1924. The anticipator regulates the furnace heating cycle time and makes temperatures more constant by reducing overshoot at end of furnace cycles. Electromechanical anticipators use the heating effect of an electric current (that flows when the furnace is on) that passes through the bimetallic coil of the thermostat. The resulting expansion of the bimetallic coil makes the furnace turn off before the thermostat reaches the set temperature. Hence the device anticipates the effect of increases in room temperature after the furnace is turned off due to residual heat in the furnace and ducting and the time lag between room temperature changes and the thermostats response to these changes.

Ten years later the first electric clock thermostat appeared[7].

In 1953 Honeywell produced the first device that we would recognize as a modern residential thermostat. The T-86 "Round" thermostat is iconic and is the most common and recognizable thermostat in North America.

[6] www.honeywell.com/sites/honeywell/ourhistory.com

[7] www.prothermostats.com/history.php

Round T-86 Honeywell Thermostat

In 1968 Honeywell produced the first combined temperature and humidity control device, in a somewhat less iconic shape!

Combined temperature and humidity control

In California, the requirement for setback thermostats in Title 24 led to more widespread adoption of these thermostats.

By 1995, a thermostat was available that would control heating, cooling, humidification, dehumidification and ventilation, while also reminding occupants to change filters. It has the push-button controls and LCD interface common to almost all current programmable thermostats.

Programmable thermostat

The basic residential thermostat has changed little in the last ten years, other than to add more convenience features such as remote controls.

After a period of relative stability, in the near future thermostats are faced with some rapid changes. Some of these changes are legislative, such as the proposed external control for demand response in California or initiated by utilities, such as Demand Response in Maryland. Other changes are in appearance, such as the increasing size of displays. Finally, many changes relate to accommodating more complex HVAC equipment (staged heating and cooling, integration with ventilation and humidity control and other household appliances) and improvements in occupant comfort. Increased complexity of equipment control, response to signals other than temperature (e.g., demand response control signals) and integration with other household devices are all issues that are currently impinging on thermostats. The thermostat as a stand-alone furnace controller will soon be a thing of the past and the additional required flexibility means that there are openings for novel approaches to designing and operating comfort controllers for homes. The following sections outline the issues to be faced by the next generation of HVAC control equipment that will replace the traditional thermostat.

2.2. Temperature Ranges and Variation

To understand the control problem we need to know: typical control temperatures (or setpoints), how close these temperatures are controlled and typical energy savings features (such as setback).

A study in the heating dominated Pacific Northwest[8] recorded hourly internal temperatures and energy end-use data in 400 single-family electrically heated houses. The significant results were:

- Bedrooms are 2°C (3.8°F) cooler than the main living space.
- Programmable clock thermostats did not change the incidence of setbacks because occupants who used the automated setback did manual setback with manual thermostats.
- Occupant reported setbacks are greater than measured - mainly due to thermal mass effects where the houses take several hours to cool down to the setback temperature.
- Average setback setting was 4°C (7°F) starting at 10:00 p.m. and ending at 6:00 a.m.
- Average measured setback was less than the setting - about 1.5°C (3°F). This difference between setback setting and measured temperatures is probably due to the time response of the house.
- No correlation of temperature settings with demographics (climate zone, number of occupants, income level, utility type, house size and house vintage).

A study[9] on self reporting found that occupant reported setbacks were greater than measured ones by an average of 1.5 °C (2.2 °F). Again this is probably explained by houses taking several hours to cool down at night. Another study in California[10] found that the mean difference between self reported and observed thermostat settings was 0.5°C (1F°) to 2°C (4°F) depending on time of day, and that heating setpoints were under-reported and cooling ones over-reported. A more recent Wisconsin study[11] found that self-reported thermostat data was a better indicator of household heating energy intensity, and is therefore a good indicator of behavior if the goal is to compare the thermostat-setting behaviors of households.

For heating only, a study of 135 homes in Iowa[12] found average setbacks of 3.3°C (5.9°F) for approximately eight hours a day.

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[8] Conner, C.C. and Lucas, R.L. 1990. Thermostat Related Behavior and Internal Temperatures Based on Measured Data in Residences. PNL-7465, Pacific Northwest Laboratory. Richland, WA.

[9] Kempton, W. and Krabacher, S. 1987. Thermostat Management: Intensive interviewing used to interpret instrumentation data. Energy Efficiency: Perspectives on Individual Behavior (Kempton and Neiman Eds.) ACEEE, Washington, DC.

[10] Lutz, J. and Wilcox, B. 1990. Comparison of Self-Reported and measured thermostat behavior in new California Houses. Proc. ACEEE Summer Study 1990, Vol. 2, pp. 91-100. ACEEE Summer Study 1990. American Council for an Energy Efficient Economy, Washington, DC.

[11] Nevius, J. and Pigg, S. 2000. Programmable Thermostats that go berserk? Taking a social perspective on space heating in Wisconsin. Proc. ACEEE Summer Study 2000, Vol. 8, pp. 233-244. ACEEE Summer Study 2000. American Council for an Energy Efficient Economy, Washington, DC.

[12] Neme, C., Hamilton, B., Erickson, P., Lind P. and Presson, T. 1996. *A Tale of Two States: Detailed Characterization of Residential New Construction Practices in Vermont and Iowa.* Proc. ACEEE Summer Study 1996, Vol. 2, pp. 173-179. American Council for an Energy Efficient Economy, Washington, DC.

Setbacks are also used during the day by families whose house is unoccupied during the day. These setbacks are similar to nighttime setbacks - a study of 212 homes in North Carolina[13] showed average daytime setbacks of 3.2°C (5.7°F) and nighttime setbacks of 2.9°C (5.3°F). In this older (pre-1990) study only 17% of thermostats were automatic and the setbacks were manually performed by the occupants, and there was no significant difference in setbacks between the automatic and manual methods.

In these studies of setback, the fraction of households actually setting back temperature varied from 36% to 83%, The fraction depended on whether the homes had automatic thermostats - the houses with automatic thermostats tended to practice setback more often. However, authors also speculated that higher setback rates also resulted form households participating in utility energy savings programs. Therefore what is the "typical" setback rate in U.S. houses is difficult to quantify, but using a value of 65% (reported in reference 12 where this question was reported specifically) is reasonable. More recent data are needed here to see if the increase in market penetration of programmable thermostats in recent years has resulted in a greater likelihood of setback being used (the most recent study reported the highest use at 83%).

In a more detailed examination of room-to-room temperature variability in 1000 British homes[14], it was found that temperature differences between the warmest rooms (living rooms) and coldest (bedrooms) was 4°C (7°F). The same study noted that houses with higher incomes had higher average temperatures, primarily because there was less variation from room-to-room with the colder rooms being less cold. In addition, houses with children home all day also showed less room-to-room variability because these secondary rooms were occupied more often, conversely households with elderly people showed greater variability. Both the Pacific Northwest and British study had mixes of central heating and zoned heating. In the Pacific Northwest, there was a mix of electric baseboard and electric forced air (both electric furnace and heat pump), woodstoves and radiant heat. For the British study, the heating was primarily hydronic with a combination of central thermostats and individual room settings on radiators, as well as individual portable electric room heaters.

From the point of view of estimating energy use and potential DR savings a key issue is knowing the actual building load and by inference the likelihood that heating or cooling systems are actually operating. This has been examined in detail for cooling systems in several studies. A key aspect of this is determining what thermostat cooling setpoints are typical. This is important when looking at the number of air conditioners that might actually respond to a DR signal (discussed later). When sizing equipment using the ACCA procedures[15] (or similar) there is the assumption of a constant setpoint of 24°C (75°F) for cooling. In humid climates there is evidence[16] that this may be too high

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[13] Turner, C,. and Gruber, K. 1990. *Residential Thermostat Management Practices: An Investigation of Setback Behavior.* Proc ACEEE Summer Study 1990, Vol. 2, pp. 151-160. ACEEE Summer Study 1990. American Council for an Energy Efficient Economy, Washington, DC.

[14] Hunt, D.R.G. and Gidman, M.I., 1982. *A National Field Survey of House Temperatures*. Building and Environment, Vol. 17., No. 2, pp. 107-124. Pergamon Press.

[15] ACCA. Manual J - Load Calculation for Residential Winter and Summer Air Conditioning. Air Conditioning Contractors of America. Washington, DC.

[16] Rudd, A. and Henderson, H. 2007. Monitored Indoor Moisture and Temperature Conditions in Humid-Climate US Residences. ASHRAE Trans., Vol. 133, Pt.1. American Society of Heating refrigerating and Air-conditioning Engineers, Atlanta, GA.

because occupants adjust thermostats downward to reduce humidity with typical setpoints of 23.5°C (74°F) and occasional operation at 18°C (65°F) or less. Conversely, in dryer climates like California a summary of several studies[17] indicated that typical operation is at 26.5°C (80°F). This is reflected in the assumed setpoints in Title 24. A more recent analysis[18] indicated that average temperature setpoints are lower at about 24.5°C 76°F. DR analyses in California need to account for higher setpoint settings because this reduces the amount of air conditioner operation and therefore also reduces the potential savings (the converse is true in humid climates with lower setpoints for humidity control). Changes in thermostat settings have a significant effect on energy use - particularly in cooling where temperature differences are usually smaller than in heating. For California homes, a 1.3°C (2.3°F) change in indoor temperature can change the energy use by about 45%[19]. A CEC/PIER Codes and Standards Enhancement Study[68] showed that a 4°F (2.2°C) step up in thermostat setting for programmable communicating thermostats (PCT) has the potential to save about 450W for each installed thermostat and more than 10% of peak residential air conditioning load (after about ten years of PCT program implementation).

For electric baseboard heaters electronic line voltage thermostats (ELVTs) offer much better control, with temperature variations measured in 27 all-electric apartments in Portland, OR of about 0.3°C (0.6°F) compared to 1.4°C (2.5°F) for standard bimetallic thermostats[20]. This tighter temperature control did not lead to any energy savings; however, there was a change in observed usage patterns: bimetallic thermostats were used more often to switch baseboards on and off manually than ELVTs - possibly due to the more even temperature control of ELVTs.

Tighter temperature control has also been found in thermostat replacement weatherization programs[21]. It was found that occupants manipulated automatic thermostats less than manual thermostats.

One investigation of historical thermostat settings based on those reported in the RECS[22] database has shown that winter temperatures have a gradual increasing trend (of 0.5°C (1°F) to 0.75°C

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[17] Brown K, Blumstien, C., Lutzenhiser, L., Hackett, B. and Huang, J. 1996. Does the Air-Conditioning Rubric Work in Residences? Proc. ACEEE Summer Study 1996, Vol. 8, pp. 11-20. American Council for an Energy Efficient Economy, Washington, DC.

[18] KEMA-XENRGY, Itron and RoperASW. 2004. California Statewide residential appliance saturation survey. California Energy Commission Report 400-04-009, Sacramento, CA.

[19] White, S. and Wilcox, B. 1996. Predicting Heating and Cooling Energy Use in New California Houses. Proc. ACEEE Summer Study 1996, Vol. 8, pp. 221-229. American Council for an Energy Efficient Economy, Washington, DC.

[20] Lambert, L. 1996. Electronic Line Voltage Thermostats: A Worthwhile Retrofit for Baseboard Heat?. Proc. ACEEE Summer Study 1996, Vol. 1, pp. 157-167. American Council for an Energy Efficient Economy, Washington, DC.

[21] Gladhart, P., and Weihl, J. 1990. *The Effects of Low Income Weatherization on Interior Temperature, Occupant Comfort and Household Management Behavior.* Proc. ACEEE Summer Study 1990, Vol. 2, pp. 43-52. American Council for an Energy Efficient Economy, Washington, DC.

[22] Energy Information Administration. Various years. *Residential Energy Consumption Survey.* Energy Information Administration, Washington, DC.

(1.5°F)) with time from 1984 to 2001[23]. Some of this may be attributable to higher setpoints that tend to be used with automatic setback thermostats and the vagaries of self reporting (in that it people may be more likely to report the heating setpoint rather than the setback temperature).

[23] Belzer, D. and Cort, K. 2004. *Statistical Analysis of Historical State-Level Residential Energy Consumption Trends.* Proc. ACEEE Summer Study 2004, Vol. 1, pp. 25-38. American Council for an Energy Efficient Economy, Washington, DC.

2.3. Changing Temperatures

Perception of thermal comfort depends not just on the current temperature, but also the rate of change of temperature. A literature review[24] of thermal comfort stated that there is good experimental evidence that if temperatures change at rates less than 0.5°C/h (1°F/h) for drifts or ramps then the environment is perceived to be at steady-state conditions.

For cyclic changes, ASHRAE Standard 55-2004[25] gives the following requirements:

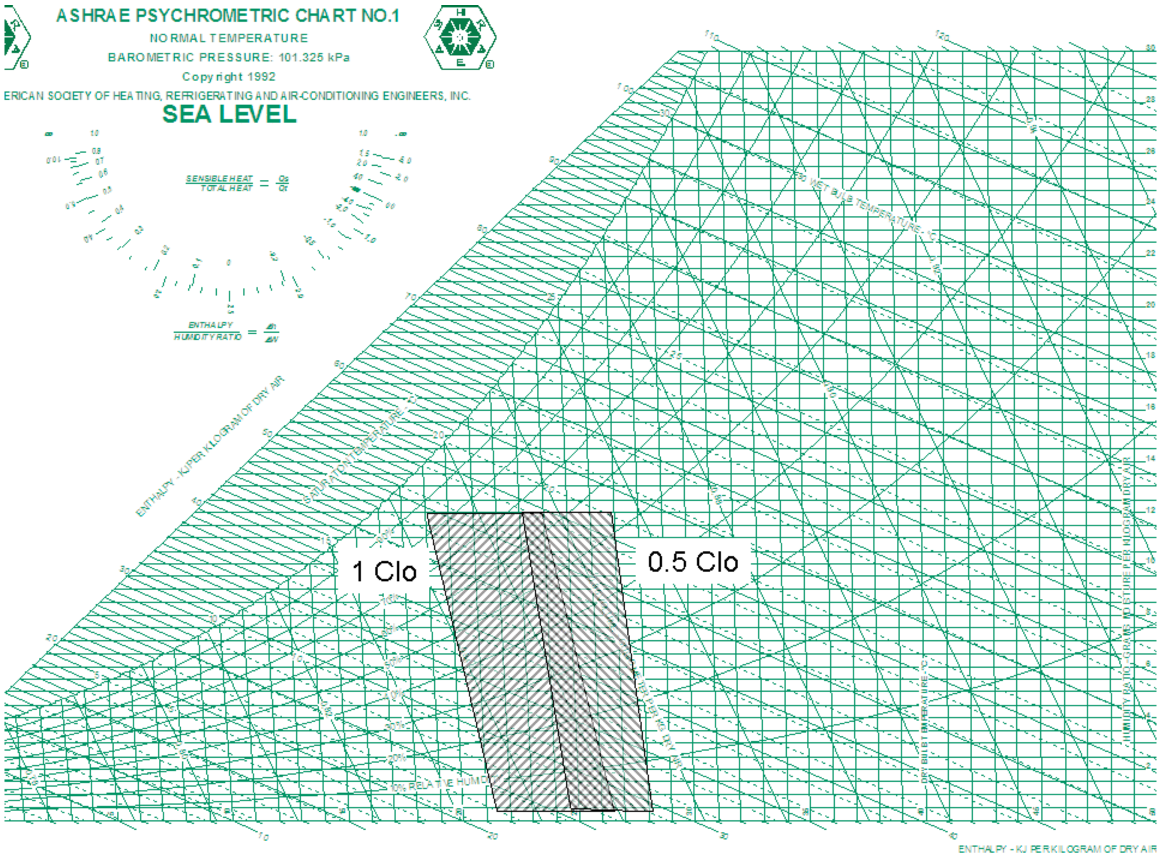
- If the period of fluctuation cycle exceeds 15 minutes then the temperature change is considered a drift or ramp rather than a cycle.
- For a cycle, the maximum allowable peak-to-peak temperature is 1.1°C (2.0°F).
- For drifts and ramps the rate of change of temperature limits depend on the length of the ramp as follows: 0.25h = 1.1°C (2.0°F); 0.5h = 1.7°C (3.0°F), 1h = 2.2°C (4.0°F); 2h = 2.8°C (5.0°F) and 4h = 3.3°C (6.0°F).

ASHRAE Standard 55-2004 discusses the interactions between air temperature, radiant environment, humidity, clothing levels, activity levels, and drafts. It also specifies acceptable operative temperature and humidity levels - often referred to as the ASHRAE "comfort zone" and seen on psychrometric charts - that also include data from ISO 7730[26].

[24] Hensen, J.L.M. 1990. *Literature Review on Thermal Comfort in Transient Conditions.* Building and Environment, Vol. 25, No. 4, pp. 309-316. Pergamon Press.

[25] ASHRAE. 2004. *ASHRAE 55-2004 Thermal Environmental Conditions for Human Occupancy. ANSI/ASHRAE Standard 55-2004.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

[26] ISO 7730:1994. *Moderate Thermal Environments - Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort.*



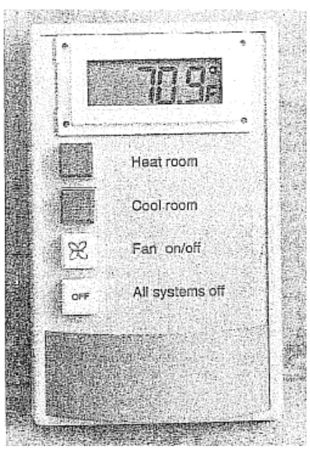
ASHRAE Standard 55 comfort zones for two clothing levels

2.4. Intelligent Thermostats

Intelligent thermostats attempt to make control even more automated than just using clocks and thermal and humidity sensors. Some rely on a user interface where for the first few days/weeks of operation the occupant makes adjustments to maintain comfort. The thermostat then learns things such as occupancy patterns for different days of the week and the variation of desired temperatures at different times of day, and the response time of the home. It uses this information to essentially self-program itself to reproduce the temporal changes in temperature desired by the occupant.

Even more sophisticated systems provide suggestions in a collaborative dialog with the user[27] in order to manage desired room temperatures while reducing energy consumption. Interaction can be by the traditional push buttons, touch screens or speech.

Another example is the *comfortstat* developed for short-term occupied rooms[28] - such as hotel rooms, that also have changing occupants on an almost daily basis and so need to learn occupant preferences quickly. Therefore, the primary innovation in the *comfortstat* was the logic for interactive setpoint adjustment to provide rapid response to guest requests. The *comfortstat* combined an occupancy sensor with four simple push buttons: heat room, cool room, fan on/off and all systems off. Another innovation was the use of a room temperature sensor that was curved and painted such that it would radiatively sense more of the room and have the appropriate surface emissivity and absorbtivity for measuring "operative temperature".



Comfortstat front panel showing four simple control buttons

[27] Keyson, D.V., de Hoogh, M.P.A.J., Freudenthal, A. and Vermeeren, A.P.O.S. 2000. *The Intelligent Thermostat: A Mixed-Initiative User Interface.* Proc. CHI 2000 Conference on Human Factors in Computing Systems. Association for Computing Machinery.

[28] Fountain, M, Brager, G., Arens, E., Bauman, F. and Benton, C. 1994. *Comfort Control for Short-Term Occupancy.* Energy and Buildings, Vo. 21, pp. 1-3. Elsevier.

2.5. Advanced Thermostat Controls

In Japan heating, cooling and ventilating controls are more sophisticated than commonly available in North America[29]. Remote controls, like those for audio/visual systems are common and they control much more than just a setpoint. As well as incorporating the features of intelligent thermostats, they have air velocity controls that change the air flow rate into the room, and air direction controls that can automatically be set to avoid cold drafts in winter in ventilating mode or before the system has fully heated up, or to blow cooled air on occupants in the summer. These features are a result of the traditional Japanese focus on heating or cooling occupants rather than spaces. They allow modern heat pump systems to imitate traditional approaches to achieving this goal. Recent innovations include programs that vary air flow and direction to mimic the natural breezes at particular geographic locations. For over 20 years Japanese thermal controls have been used that do not display a temperature number - instead the occupant selects thermal comfort criteria such as "I feel cold", "I feel comfortable" or "I feel hot" to select buttons on a controller. These criteria represent the psycho-physical state of the occupant, rather than simply the air temperature. Controller manufacturers have developed pre-programmed protocols relating to this perception of thermal comfort that change depending on the room. Cultural and technical preferences partly explain the differences in systems found in Japan and North America. Although the controls in Japan are more sophisticated, the occupants seem no more adept than those in North America. In a survey[27] of 20 Japanese residents using these systems a majority reported that they did not understand or use all of the available control options.

For ventilation cooling controls an advanced controller has been developed in California (NIGHTVENT)[30] that includes new concepts for thermal comfort where occupants are allowed to select the desired minimum indoor temperature to produce a desired maximum afternoon indoor temperature. The controller also incorporates "soft keys" where a minimum number of push buttons can be reprogrammed to perform multiple tasks with a display that changes to indicate the current status of each button. Lastly, this controller introduces an element of game playing by allowing the user to set upper and lower temperature limits and receive feedback from the controller such as "A/C will run".

[29] Fuji, H. and Lutzenhiser, L. 1992. *Japanese Residential Air-Conditioning: Natural Cooling and Intelligent Systems.* Energy and Buildings, Vol. 18, pp. 221-233. Elsevier Sequoia.

[30] Springer, D., Loisos, G. and Rainer, L. 2000. *Non-Compressor Cooling Alternatives for Reducing Residential Peak Load*. ACEEE Summer Study 2000, Vol. 1, pp. 319-330. American Council for an Energy Efficient Economy, Washington, DC.

Display screens for NIGHTVENT

An experimental thermostat was designed to adjust heating levels using a proxy to sensing occupancy: lighting levels. Thermostats equipped with integrated light sensors were evaluated in 23 electric baseboard heated homes in New England[31]. These thermostats used automated setbacks depending on light levels. Although there was a potential to save energy by automating the set-back, occupants complained of light based interactions that resulted in unintended consequences, for example, people who watched TV at lowlight levels found that this initiated the setback. Another issue was that bathrooms would be too cold in the morning. These thermostats did not have automated clock setback and some occupants were disappointed to not have automated daytime setback when they were not in the house. These occupant interactions indicate that innovations such as these light sensitive setback thermostats are not appropriate for all users. This limit of applicability can have an impact on selection of technologies for energy saving programs.

Heat pumps require more sophisticated thermostats in order to efficiently switch from normal operation to electric resistance back-up heaters. A heating schedule involving temperature setbacks is generally not recommended because the recovery from setback requires additional capacity, which must typically be supplied by lower-efficiency electric resistance heat[32]. Reliance on resistance back-up heating also presents greater peak demand on winter mornings. (This is less of less concern in California because heat pumps are relatively rare.) The shift to resistance back-up can be minimized by using adaptive recovery thermostats, which gradually increase thermostat settings.

Commercial buildings must meet different heating and cooling requirements because schedules are more regular and internal gains may be higher than in homes. Some designs allow each person to modify their conditions via a link on his or her computer which, in turn, passes the preferences to the building's energy management system. Sophisticated software using autonomous agents is used to optimize system operation - introducing concepts such as the "caring building"[33]. It is not clear how this will translate into residential buildings where occupants are more likely to wander from location to location rather than stay in the proximity of a single computer.

One feature likely to be present in many thermostats in the near-future will be communications capabilities. A communications capability will allow the thermostat to communicate via Bluetooth, wifi, or Ethernet to other equipment (including mobile telephones), computers, or the utility. In new homes, the savings from wireless communication may allow consumers to spend more on feature-laden thermostats.

Some researchers have investigated some very complex home automation systems[34] and certainly the technology and software exist to create systems that are integrated with the electricity

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[31] Titus, E. 1996. *Advanced Retrofit: A Pilot Study in Maximum Residential Energy Efficiency.* Proc. ACEEE Summer Study 1996, Vol. 1, pp.239-245. American Council for an Energy Efficient Economy, Washington, DC.

[32] Bouchelle, M., Parker, D., Anello, M. and Richardson, K. 2000. *Factors influencing space heat and heat pump efficiency from a large-scale residential monitoring study* Proc. ACEEE 2000 Summer Study, Vol. 1, pp. 39-52. American Council for an Energy Efficient Economy, Washington, DC.

[33] Zeiler, W. and Kamphuis, R. 2006. *Caring Buildings; User Based Indoor Climate Control.* REHVA Journal, 4/2006, pp. 13-18. Federation of European Heating and Air Conditioning Associations (www.rehva.com)

[34] Spinellis, D. 2003. *The Information Interface: Consolidated Home Control.* Personal and Ubiquitous Computing, Vol. 7, pp. 53-69. Springer-Verlag, London.

distribution grid, weather information (via the interweb or radio transmission), other household appliances and services: ventilation, humidity, hot water, lighting, gas fireplaces. However we need to pause and think about if most users actually want any of this. Particularly when there are some simple features that users would like to have that are currently not available, e.g., timers for room air-conditioner operation[35].

Integration will clearly present problems. Even before we integrate ventilation systems into our "comfort controllers" we need to be aware of existing installation issues. For example the simplest mechanical ventilation system that satisfies ASHRAE 62.2 requirements for residential mechanical ventilation is an exhaust only ventilator (EOV). Field surveys have found that EOVs are correctly programmed in less than half of installed systems[36].

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[35] Kempton, W., Feuermann, D. and McGarity, A.E. 1992. *"I always turn it on super": user decisions about when and how to operate room air conditioners".* Energy and Buildings, Vol. 18, pp. 177-191. Elsevier Sequoia.

[36] Shapiro, A., Cawley, D., King, J. 2000. *A Field Study of Exhaust Only Ventilation System Performance in Residential New Construction in Vermont.* Proc. ACEEE Summer Study 2000, Vol. 1, pp. 261- 272. American Council for an Energy Efficient Economy, Washington, DC.

2.6. The Cost of Advancing Technology

As the modern thermostat has developed from the 1950's Honeywell round to electronic programmable units, the cost of the controls has increased. Electromechanical thermostats (originally based on mercury switches) are inexpensive ($20-$30) and their simplicity can be attractive to contractors and users. Electronic programmable thermostats have a greater range and cost $30 to $150 depending on brand and features[37]. There is some overlap with the most expensive electromechanical thermostats costing about the same as an inexpensive electronic programmable thermostat, which indicates that it is possible to increase features without necessarily increasing price. However the declining cost of electronic controls virtually assures that electromechanical thermostats will soon disappear, while electronic thermostats will be standard at no additional cost. Of course the cost will increase as new features, controls, and sensors are introduced. These cost increases will be weighed by consumers against the value of additional features. However, consumers will have limited options because building codes, utility programs, and other voluntary programs (like Energy Star) dictate thermostat specifications. An exception to this simple economics is when building codes and standards require certain aspects of thermostat performance that can only be achieved with particular thermostats, e.g., Energy Star requirements for setback and temperature swing, or proposed DR signal response ability in California. In these cases, the code and standard setting bodies will have to decide if the additional cost is outweighed by potential energy or demand savings. One issue is the potential to reduce future upgrade costs. A communicating thermostat can provide different features (for example, user-selected options or utility program requirements) that can be downloaded without any cost in the future.

Homes are already beginning to incorporate extensive communications, causing the thermostat to become just one element of linking to a complete whole-house integrated control system [38]. This system may simultaneously oversee and operate ventilation, HVAC, lighting, and window shading. The rise of these larger sensing and controlling systems obscures the economic decisions on the cost of thermal comfort controls. The skills required to program and operate complex whole-house controls can easily outpace the occupants' ability to understand and operate them.

[37] Morose, G. 2003. *A review of thermostat energy efficiency and pricing.* Lowell Center for Sustainable Production. University of Massachusetts, Lowell.

[38] Spinellis, D. 2003. *The Information Interface: Consolidated Home Control.* Personal and Ubiquitous Computing, Vol. 7, pp. 53-69. Springer-Verlag, London.

2.7. Human Factors

The use of a thermostat as an on/off switch rather than a temperature controller is a common approach to operating heating and cooling systems and has been estimated to be used by 25% to 50% of U.S. households. Different "theories of operation" have been proposed. When the user believes that the difference between the current room temperature and the manual thermostat setting is proportional to the rate of heating or cooling (an analogy is made to an automobile gas pedal) this method of operation is referred to as the "valve theory". In contrast, the "feedback theory" consists of setting a fixed setpoint. Although the valve theory bypasses much of the functionality of a programmable thermostat it can be highly practical in day-to-day use[39,21].

The impact of consumer misunderstanding of thermostat behavior partly explains the differences in observed and predicted energy savings. Several studies found that homes relying on programmable thermostats consumed more energy than those where the occupants set the thermostats manually[40]. These results do not prove that people who setback manual thermostats were using the valve theory but it does show that providing new technology, by itself, may not actually change energy use or comfort. Individual technologies may invoke different responses and need to be evaluated on their individual merits and responses. A more recent larger scale (about 7000 households) billing analysis study[41] concluded that savings of about 6% were attributable to automatic thermostat use. This study speculated that other studies had different results because of small sample size and, probably more critically, they were not in heating dominated climates (which was not entirely accurate).

Occupants of the same house often have different desired temperature settings. A Florida study[42] observed that different family members wanted temperatures set over a relatively large 5°C (10°F) range. In addition, there were distinct groups of operating modes - half the houses used constant setpoints, and others used manually varied setpoints. The variability in indoor temperatures combined with other occupant variability (such as using ventilation cooling and other appliance loads) led to a factor of about 4:1 in AC energy consumption in ten identically constructed homes. The authors noted that contractors might oversize the air conditioning equipment to avoid callbacks from occupants with much higher internal loads or desire for a lower temperature than used in standard sizing calculations.

This conflict between different household members can lead to reductions in potential energy savings (although it is not clear to what degree this is so) and some researchers have proposed the

[39] Kempton, W. 1986. *Two Theories of Home Heat Control*. Cognitive Science, Vol. 10, pp. 75-90.

[40] Sachs, H. 2004. *Programmable Thermostats*. ACEEE, Washington, DC.

[41] RLW Analytics. 2007. *Validating the Impact of Programmable Thermostats*. RLW Analytics, Middletown, CT.

[42] Parker, D., Barkaszi, S, Sherwin, J, and Richardson, C. 1996. *Central Air Conditioner Usage Patterns in Low-Income Housing in a Hot and Humid Climate: Influences on Energy Use and Peak Demand.* Proc. ACEEE Summer Study 1996, Vol. 8, pp. 147-160. American Council for an Energy Efficient Economy. Washington, DC.

development of goal setting strategies for occupant interactions with the thermostat to reduce these effects[43].

A large scale (3094 participants aged 15-74) study in Finland[44] showed significant differences in thermal comfort, temperature preference and thermostat use between genders. "Females are less satisfied with room temperatures than males, prefer higher room temperatures than males, and feel both uncomfortably cold and uncomfortably hot more often than males. Although females are more critical of their thermal environments, males use thermostats in households more often than females.". To further complicate the task of a thermostat in keeping all occupants happy, "36% of those who live with a spouse said that there are different preferences for room temperature in their household." And 65% of the time it is women who want a higher room temperature. This Finnish study also found that there were no changes in control actions (to ask for the room to be warmer or cooler) if occupants knew the measured room temperature, or if a recommended room temperature was given. This may have important consequences for the design of thermal comfort control interfaces that currently display a temperature and the control buttons are labeled (and act) to change the displayed temperature. It is therefore likely that users change thermostat settings so they are comfortable and that the resulting temperature on the display is not useful information.

Problems with the interface between the controls and occupants arise because the occupants do not know how to use them successfully (with the emphasis on *successfully*)[45]. Alternatively, ambiguous lights or symbols on the thermostat confuse the users or lead them to do the opposite of what they want. Thermostats controlling heat pumps offer compelling examples of potential confusion:

The indicator lights on some thermostats glow red when in heat pump mode and green when using electric resistance "emergency" heat. The color of the signal has fixed connotations for the user (green=energy efficient vs. red=emergency) that in this case are the reverse of actual operation.

The operating mode selector is set to the far right for cooling and far left for electric resistance heat. The operating mode we want for energy efficiency is the middle setting. However most users switch all the way to the left for heat - bypassing the middle option.

A somewhat academic (in the sense that it places possibly unrealistic expectations on potential users) 3-I principle of empowerment has been suggested[46] as guidance for future work on interfaces:

- **Insight**. Users must understand the way a building works and the consequences of actions.
- **Information**. Users must learn to use controls with the help of feedback
- **Influence**. Users who have insight and information need to be given individual choices.

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[43] McCalley, L. and Midden, C. 2004. *Goal Conflict and User Experience: Moderators to the use of the clock thermostat as a device to support conservation behavior.* Proc. ACEEE Summer Study 2004, Vol. 7, pp.251-259. American Council for an Energy Efficient Economy, Washington, DC.

[44] Karjalainen, S. 2007. *Gender Differences in Thermal Comfort and use of Thermostats in Everyday Thermal Environments*. Building and Environment, Vol. 42, pp. 1594-1603. Elsevier.

[45] Karjalainen, S. and Koistinen, O. 2007. *User Problems with Individual Temperature Control in Offices*. Building and Environment, Vol. 42, pp. 2880-2887. Elsevier.

[46] Wyon, D.P. 2000. *Individual Control at Each Workplace: The Means and Potential Benefits.* Creating the Productive Workplace (D. Clements-Croome Ed.), pp. 192-206. E & FN SPON, London and New York.

Some progress has been made in establishing consistent power controls in IT equipment.[47] It is increasingly likely that a person will find the terms, symbols, and procedures to shift a computer into energy-saving sleep mode similar from one computer to the next.

When occupants are dissatisfied with thermal conditions or ventilation they will adjust thermostat or open/close windows and doors. A study of teachers showed that more than half were adjusting thermostats in their classrooms at least once a week[48].

More complex user interfaces are not always associated with negative impacts. In replacement of line voltage thermostats on baseboard electric heaters with electronic thermostats, 85% of occupants preferred the new thermostats saying that they liked the improved thermal control, ease of setting and the digital display of actual temperature and setpoint[49].

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[47] See http://eetd.lbl.gov/Controls/

[48] Heschong, L. and Wright, R. 2002. *Daylighting and Human Performance: Latest Findings*. Proc. ACEEE Summer Study 2002, Vol. 8, pp. 91-104. American Council for an Energy Efficient Economy, Washington, DC.

[49] Johnson, R., Bhagani, D. and Carlson, S. *Measured Impact of Mechanical Thermostat Replacement.* 2000. Proc ACEEE Summer Study 2000, Vol. 1, pp. 137-148. American Council for an Energy Efficient Economy, Washington, DC.

Occupant interviews in Wisconsin[11] uncovered the following reasons for not using a programmable thermostat:

- Occupants did not believe the savings estimates provided by a Home Energy Rating Audit.
- The payback or potential increase in convenience was not worth the cost.
- Programming the thermostat would be too much "hassle".
- Most heating comes from an alternative source (e.g., wood stove).
- They had heard of programmable thermostats that went "berserk" and overheated a house.

The role of education in changing human behavior should not be overlooked. A study for New York State's Weatherization Assistance Program[50] showed that participants who were given energy education training had greater savings (almost 60% higher); however, the persistence of savings was the same for trained and non-trained participants.

A study of 283 residents in the Pacific Northwest[51] found that holding a positive attitude toward energy conservation is probably not linked to energy conserving behaviors but, like "mom, apple pie, and the flag," is a socially desirable thing in which to believe. This study also concluded that attitudes toward comfort were more important than attitudes towards conservation in determining conservation behavior.

As with other energy related issues, there can be differences between occupants who rent and those who own. Renters may have lowered expectations for comfort because they do not expect to have control. The classic example is apartment buildings where individual apartments do not have any controls and occupants resort to other strategies, such as changing clothing or opening windows. The following studies looked specifically at renters/low-income occupants.

Older people have special thermal comfort needs and habits. A study of energy use among low-income elderly people in California[52,53] found that several occupants never touched the thermostat for fear of doing the wrong thing. Thermostat settings were also influenced by the amount of disposable income available to residents. Although all the residents were classified as low income (less than $300/month) some residents had considerable savings and could afford to operate the heating and cooling systems more often and/or adjust thermostat settings so they could be more comfortable. At least thirty percent of residents reported having trouble with the thermostat and probably more thought they were operating the thermostat correctly but were not. The thermostats were difficult to understand and the letters and symbols were difficult to read. Furthermore the design of the

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[50] Harrigan, M and Gregory, J. 1994. *Do Savings from Energy Education Persist?* Proc. ACEEE Summer Study 1994, Vol. 1, pp. 65-73. American Council for an Energy Efficient Economy, Washington, DC.

[51] Peters, J. 1990. *Integrating Psychological and Economic Perspectives of Thermostat Setting Behavior.* Proc. ACEEE Summer Study 1990, Vol. 2, pp. 111-118. American Council for an Energy Efficient Economy, Washington, DC.

[52] Diamond, R.C. 1984. *Comfort and Control: Energy and Housing for the Elderly.* A UERG California Energy Studies Report. UER-129. University-wide Energy research Group, University of California.

[53] Diamond, R.C. 1984. *Energy Use Among the Low-Income Elderly: A Closer Look".* Proc. ACEEE Summer Study 1984. American Council for an Energy Efficient Economy, Washington, DC. LBL-17593.

controls was poor - on the far right was cooling, with "off" and "heat pump" modes in between and "emergency" electric resistance heat to the far left. When the occupants wanted heat, they moved the switch to the far left as this was the intuitive position. This was a case of occupants being unfamiliar with how a specific technology (in this case a heat pump) operates. Also, the electric resistance heat would be activated upon a change in thermostat setting - e.g., in the morning after nighttime setback. The wide spread of temperatures at which occupants were comfortable, the range of income available to pay for heating and cooling together with the different interactions with the controls led to a wide range of temperatures in the houses from 70°F to 85°F in winter and 72°F to 90°F in the summer. Issues of fiscal and energy conservatism were also noted because the occupants could tell when neighbors operated their heating and cooling systems and occupants passed judgment on each other based on how much they heated or cooled.

A study of evaporative cooling retrofits in public housing in Sacramento[54] further reinforces issues of how unfamiliar technologies (in this case use of evaporative cooling rather than not cooling or using conventional refrigerant based DX systems) need complimentary changes in thermostat use. The systems had lights that came on at the start of a cycle to indicate that pads were being wetted in the evaporative cooler, but before cooling was available. This was not clear to residents and one of them turned off the system when the light came on (possibly thinking it was an idiot light indicating a system problem). Several occupants were initially not happy with the cooling provided by their systems - but once shown how to correctly operate the thermostat they were satisfied. Interviews showed that occupants had no interest in tinkering with thermostats themselves to optimize performance - generally they just turned systems on and off.

[54] Diamond, R., Remus, J. and Vincent, B. 1996. *User Satisfaction with Innovative Cooling Retrofits in Sacramento Public Housing.* Proc. ACEEE Summer Study 1996. Vol. 8, pp. 21-20. American Council for an Energy Efficient Economy, Washington, DC.

2.8. Room Air Conditioners

Room air conditioners are self-contained units that are commonly installed in windows or through the walls. The controls for room air conditioners are fundamentally different from central air conditioners. Rather than a numerical temperature display there is a knob generally labeled with the word “cooler” and a directional arrow. Some units include a numerical scale - with increasing numbers indicating more cooling (which could be a cause for user confusion as higher temperature may be associated with high numbers). Others include labeling of an “economy” range. This knob operates as a thermostatic control, but without the traditional display of a numerical value of temperature. Other controls include a fan speed switch, an outdoor air setting, and for some units high/low settings for cooling.

Studies of the operation of individual room air conditioners has led to several insights on human interactions with controls and the influence of non-economic factors on air conditioner operation. A study of room air conditioners in apartment buildings[55] found that:

- Physically similar apartments had energy use vary by two to three orders of magnitude even though the spread in indoor temperatures was only 2.4°C to 3.7 °C (4.3°F to 6.7°F). This was primarily due to many occupants manually operating their air conditioners during peak conditions. This is an important issue for peak demand and demand response because this mode of operation (only turning systems on at peak) maximizes peak demand and removes the ability if these systems to respond in a user acceptable way to automated demand response signals.
- Even though residents were not billed separately for electricity use, many of them limited air conditioning use on the basis of non-economic issues: “daily schedule, folk theories about how air conditioners function and the bodies heat tolerance, personal strategies for dealing with all machines, and beliefs and preferences concerning health, thermal comfort, and alternative cooling strategies”.
- Occupants very rarely allowed the thermostat to control operation. Instead, people tuned the unit on and off manually, and they turned them on more often during hot periods thus mimicking in some ways partial thermostatic control.
- Occupants would like operating features that are not currently available, such as air conditioners that will turn off after a fixed time (like bathroom heat lamps or ventilation fans).

A second category of small air conditioners, typically called “mini-splits”, fulfill the same role a room air conditioners but have separate interior and exterior components, connected by a refrigerant line. Mini-split systems are standard in East Asia and, increasingly, in Europe but are rare in US homes. However they are likely to become more common because they can better match reduced loads in low-energy homes. They also have superior de-humidification performance. Mini-splits (and their controls) will require consideration as we look to the future.

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[55] Kempton, W., Feuermann, D. and McGarity, A.E. 1992. *“I always turn it on super”: user decisions about when and how to operate room air conditioners”.* Energy and Buildings, Vo. 18, pp. 177-191. Elsevier Sequoia.

2.9. Hydronic Controls

Hydronic systems tend to have longer response times than forced air systems and therefore may benefit from the use of more advanced control strategies[56]. A few examples are:

- Replacing the common proportional control with a proportional integral (PI) or proportional-integral-derivative (PID) control strategy.
- Linearizing algorithms to compensate for non-linearity in control valves.
- The use of feedback systems to compensate for the time varying dynamics of control valves due to disturbances such as the varying feed temperatures in water heated systems.
- Automatic tuning of the controller to the house and system thermal time response characteristics.
- Using feed-forward control based on measurement of system temperatures. A common controller strategy in water heated systems is to let the feed temperature to radiators be a function of outdoor temperature.

The referenced study found that there were potential energy savings and tighter temperature control using feed-forward controls, however, the study stressed the need for good thermal models of the building and controller. In practical terms this probably requires some type of adaptive logic that over an initial period of operation automatically generates a suitable model. The question is then if the performance until the model is developed is acceptable to the occupants.

[56] Thomas, B and Soleimani-Mohseni, M. 2002. *Intelligent Thermostats Save Energy and Give Improved Control Performance.* Proc. ACEEE Summer Study 2002, Vol. 7, pp.245-257. American Council for an Energy Efficient Economy, Washington, DC.

2.10. Thermostats Outside the United States

Few countries rely on forced air heating/cooling systems as much as the United States. Instead, homes in other developed countries rely on boilers, hot water, district heating, spot heating, and other methods to provide space heating and mini-split air conditioners to provide cooling. The controls for these systems sometimes differ, too.

2.10.1. Japan

Technical innovations in Japanese cooling and heating technologies have influenced the design and features in the "thermostat". The most important innovations have been the mini-split air conditioner, variable speed motors for both the air blower and the compressor, and microprocessor controls.

The traditional goal in Japanese homes is to heat or cool the person rather than the room or all of the home. Heating is generally supplied by portable kerosene and gas room heaters (both vented and unvented to outdoors). A typical home will have one to five of these units. Living rooms in some homes have heated carpets (using electric resistance heat). Each of these devices will have their own controls, typically on the heater itself. These units typically regulate output and sometimes are thermostatically controlled.

Air conditioners—which double as heat pumps--are present in essentially all Japanese homes. About 95% of them are wall-mounted mini-splits[57]. These units are typically operated individually, although a single outdoor compressor may serve one or more of the room units. As a result, the control for each room unit operates independently.

All mini-split air conditioners are operated via a remote control (see examples below). The remote control also serves as the unit's thermostat but often do much more than simply regulate temperature. For example, one control has only 4 buttons and these are used to adjust temperature and fan speed.

[57] Nakagami, Hidetoshi. 2007. Ph.D. Dissertation "Research on Residential Energy Consumption in Japan", Department of Architecture, The University of Tokyo, Tokyo.

However, most controls have many more functions. The control on the left, for example, has 12 buttons. These buttons are used to adjust:

- temperature
- dehumidification
- fan speed (“wind”)
- fan direction and distribution
- fan pattern
- timer
- special sleep schedule
- filter clean

Examples of Japanese Remote Controls

De-humidification can be adjusted with the variable speed compressors and fans . The air distribution is controlled through computer-controlled, vanes mounted on the wall unit. Some remote controls communicate the location of the remote to the wall unit. The most sophisticated units keep track of the remote control location with respect to the wall unit. In this way, the warm or cold air can be directed toward a specific location (assuming that the occupant keeps the thermostat close to his or her actual location). It can also be delivered with any of several pre-preprogrammed patterns (random, low speed punctuated by periods of high speed, crescendos, etc.)

The strategy of heating and cooling the person rather than the room reflected in these controls are supported in the results from a recent internet survey[58] of operating hours (based on 7778

[58] Yasumoto-Nicolson, Ken "Japanese Air Conditioner Usage." What Japan Thinks. 2007. http://whatjapanthinks.com/2007/05/30/japanese-air-conditioner-usage/ .

respondents) that posed the question: “How many hours per day do you operate your air conditioner/heater”?

How Many Hours per Day Do You Operate Your Air Conditioner?	Summer*	Winter*
Up to two hours	12%	16%
Up to four hours	20%	12%
Up to six hours	23%	9 %
Up to eight hours	17%	7%
Up to twelve hours	14%	5%
Up to eighteen hours	7%	2%
Up to twenty-four hours	3%	1%
Forgotten, don’t use during that season	4%	47%

*Results rounded to the nearest 1%

A quarter of the respondents use the heater less than four hours per day. In the summer, about a third of the respondents claim to use the air conditioner less than four hours per day. Thus, the dominant usage pattern is occasional, and presumably intermittent, operation. About 23% of the respondents—and these were a tech-savvy group—reported dissatisfaction with the thermostat including inability to set temperature precisely enough (this is no surprise since nearly third also expressed dissatisfaction with the air conditioner’s ability to cool the room) or the functions were difficult to use.

Discussions with researchers familiar with the design of these (and Korean) remote controls indicate that relatively little attention has been devoted to the user interface. One measure taken to reduce confusion with multiple buttons and inadvertently punching the wrong button was the installation of sliding covers, leaving only the power on/off button and temperature controls exposed.

In contrast, considerable research was directed towards creating effective thermal comfort. Manufacturers created numerous special heating and cooling programs for different activities (notably sleeping) so as to maximize comfort from a wall unit. The manufacturers also learned to display a winter temperature 2°C (4°F) cooler than reality in order to compensate for thermal discomfort caused by air flow.

Network connections to air conditioners are beginning to appear. Panasonic demonstrated a mobile phone connection in 2003 [59], but it's not known if it has entered the market in any significant way. Korean designers have proposed linking individuals' mobile phones to the home's heating and cooling system so that the desired thermal conditions can "follow" the individual around the home.

2.10.2. *Europe and the United Kingdom*

Most of the heating in Europe is via hot water to radiators and convectors. The hot water comes from individual boilers (heated by gas, oil, or wood pellets) or via district heating systems. Air conditioning is rare in Northern Europe either from room or central systems. Thus, the primary role of thermostats is to control the space heating system. The controls include programmable thermostats, sometimes combined with thermostatic radiator valves (TRVs) that allow heating in only selected rooms. Some units can regulate both air temperature and floor temperature (because some heating may be supplied through a heated floor). Ventilation is typically controlled separately.

European Programmable Heating Control Thermostatic Radiator Valve

The UK has undergone a rapid transition to central heating as natural gas has become widely available. Typically a boiler is used to provide hot water for radiator or floor heating. Central heating and programmable thermostats are therefore a relatively new phenomenon. About 75% of the homes have the package of programmable thermostat and some TRVs.

The UK's Building Research Establishment surveyed the effectiveness of home heating controls in the UK[60]. It found widespread misunderstanding of the programmable thermostat's functions as well as design errors that encourage wasteful practices. The findings most relevant to the US conditions include:

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[59] ZDNet Asia 2003, "Panasonic edges closer to smart home reality"

http://www.zdnetasia.com/news/hardware/0,39042972,39141008,00.htm

[60] Rathouse, K and Young, B., 2004, RPDH-15, The Use of Domestic Heating Controls, Building Research Establishment, UK.

- Some people avoided using their programmable thermostats altogether. Occupants explained that they found the thermostats tricky to use or because they believed that it was more efficient to leave their heating running all the time.
- People who did use their programmable functions were generally flexible and used their heating controls to respond to changes to their routines. However, there were also some instances of people sticking rigidly to the programmed times.
- Use of programmable thermostats varied widely. At one extreme, people adjusted them whenever they felt too hot or too cold, going out, coming in, going to bed or getting up in the morning. At the other extreme people did not adjust them at all, but this was very rare.

The survey found that occupants had numerous misconceptions regarding the functioning of heating controls. These included believing that the room thermostat is simply an on/off switch or thinking that it works like a dimmer switch. Finally, the survey solicited the occupants' opinions of the programmable thermostats. The three most important comments were:

- The buttons were too small. This was seen as important by both old and young people.
- Programmable thermostats were too complex.
- The position and location of the thermostat was important. Many people complained that the thermostats were placed too high, too low, out of reach, somewhere dark, or partly hidden.

Relatively few people grasped the relationship between thermostat settings and energy consumption. Most people understood how use of heating impacts on energy consumption; however, some did not realize that turning down the thermostat would reduce energy consumption. There was also considerable debate about whether intermittent or continuous use of central heating is more efficient.

These findings illustrate how the issues surrounding programmable thermostats, and HVAC controls in general, are common across the cultural boundaries as well as the differences in heating/cooling equipment between the US and UK. Like the North American research results, this study indicated that more effective use of programmable thermostats requires modifications in design, installation, and education. Like the studies in Finland by Karjalainen[43,44], this UK study found gender differences, such as some women indicating that setting the thermostat should be left to men.

A feature often used in the UK but uncommon in the US was the BOOST button. The BOOST button overrode the setback or advanced the thermostat to the next program setpoint. This feature allowed people with irregular schedules to conveniently depart from a programmed schedule without complex re-keying.

The study concluded with two recommendations relevant to the development of future controls:

- Redesign products to include large buttons. This will benefit people generally, not just older and disabled people.
- Make available a variety of products of different complexity to suit different needs. Indicate the complexity so that an appropriate product can be selected.

3.0 California Building Energy Code Requirements: Title 24

In California, building energy use is regulated via California's Building Codes. The energy efficiency of buildings is regulated by: "Title 24, Part 6, of the California Code of Regulations: California's Energy Efficiency Standards for Residential and Nonresidential Buildings"[61], also known as Title24. Appliances (including furnaces and air conditioners) are regulated by: "California Code of Regulations, Title 20, Appliance Efficiency Regulations"[62], also known as Title 20. Currently, Title 20 does not have thermostat requirements for HVAC systems.

Title 24 has specific requirements for thermostats. The Title 24 Residential Compliance Manual[63] currently (2005 regulations) requires the use of automatic setback thermostats for central systems. An exception is allowed if the computer performance approach is used with a non-setback thermostat and the system is one of the following non-central types:

- Non-central electric heaters
- Room air conditioners
- Room air conditioner heat pumps
- Gravity gas wall heaters
- Gravity floor heaters
- Gravity room heaters
- Room air conditioners.

For heat pumps a "smart thermostat" is required that minimizes the use of electric resistance heating.

The Title 24 Alternative Calculation Method[64] (ACM) has tabulated standard values for setback thermostat settings as shown in Table 1. Additional values are given for living and sleeping zones for zoned systems. The switch from heating to cooling is determined from a seven day running average outdoor temperature. When this running average is less than or equal to 60°F then the building is considered to be in heating mode and if greater than 60°F the building is in cooling mode.

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[61] California Energy Commission. 2005. Title 24, Part 6, of the California Code of Regulations: California's Energy Efficiency Standards for Residential and Nonresidential Buildings. California Energy Commission, Sacramento, CA.

[62] California Energy Commission. 2005. California Code of Regulations, Title 20, Appliance Efficiency Regulations. California Energy Commission. Sacramento, CA.

[63] California Energy Commission. 2005. *2005 Building Energy Efficiency Standards Residential Compliance Manual*. CEC-400-2005-005-CMF. California Energy Commission, Sacramento, CA.

[64] California Energy Commission. 2005. *Residential Alternative Calculation Method (ACM) Approval Manual for the 2005 Residential Energy Efficiency Standards for Residential and Non-Residential Buildings*. California Energy Commission, Sacramento, CA.

Table 1: Whole House Standard Thermostat settings for Title 24		
Hour	**Heating °F**	**Cooling °F**
1	65	78
2	65	78
3	65	78
4	65	78
5	65	78
6	65	78
7	65	78
8	68	83
9	68	83
10	68	83
11	68	83
12	68	83
13	68	83
14	68	82
15	68	81
16	68	80
17	68	79
18	68	78
19	68	78
20	68	78
21	68	78
22	68	78
23	68	78
24	65	78

Title 24 includes exceptions to these setback requirements:

"*Setback Thermostat Exceptions*. Certain types of heating and/or cooling equipment are excepted from the mandatory requirement for setback thermostats, including wall furnaces and through-the-wall heat pumps. If setback thermostats are not installed, then the ACM shall model the *Proposed Design* with the standard thermostat schedule, except that the heating mode setback setpoint shall be 66°F. In cases where setback thermostats are not mandatory but nonetheless are installed by the builder, the ACM shall model the *Proposed Design* using the standard heating setback setpoint of 65°F. The *Standard Design* always assumes the setback schedule shown in Table R4-1."

These setback schedules have important implications for energy use and equipment sizing. From the energy use perspective, they are typical of setbacks developed to save energy because they reduce indoor-outdoor temperature differences. For equipment sizing, extra capacity is required to maintain these setpoints - when heating up in the morning for heating or for the afternoon pulldown for cooling. It is debatable how much effect this has on equipment sizing. The industry standard methods for calculating building loads from ACCA[65] assume constant setpoints, however, the ACCA sizing manual[66] does allow for excess capacity to be installed.

[65] ACCA. Manual J - Load Calculation for Residential Winter and Summer Air Conditioning. Air Conditioning Contractors of America. Washington, DC.

[66] ACCA. Manual S - Residential Equipment Selection. Air Conditioning Contractors of America. Washington, DC.

4.0 Demand Response

Thermostats are a key component in California's plans to reduce state-wide peak electricity demand through control of air conditioning systems. The case for using residential thermostats to control peak demand via reduced air conditioner operation is summarized as follows[67]:

- Potential demand reductions are large - 20% (10 GW)
- Residential customers prefer AC curtailment to curtailment of other loads (examples might be plug loads such as television, computers, refrigerators, washing machines, dryers, etc.)
- Setpoint adjust is more equitable than direct compressor control that gives greater benefits to oversized systems.

The current plan for the 2008 California Buildings Energy Efficiency Standards [68] is to use programmable communicating thermostats (PCTs) that would receive a signal at peak times to change thermostat settings. In summer, the thermostat increases the setpoint by 4°F (2.2°C) and the signal would be sent between 2 p.m. and 6 p.m. In winter, the supplementary resistance heat would be disabled.

The principles behind PCTs as proposed for the 2008 Building Energy Efficiency Standards in California are:

- A common interface and signal format for all of California
- Retail purchase - consumer owned, operated and maintained

A summary of the PCT vision for California[69] shows how PCT technologies will support system reliability, dynamic pricing and incentive programs:

- **Mandatory load control**. This is a last resort to prevent power outages and cannot be overriden by customers.
- **Dynamic pricing**. Allows customers to reduce their energy bills through voluntary load reduction.
- **Incentive Programs**. Pay for participation and/or performance

A core idea is that PCTs will allow customers to pre-program responses to critical/peak events. This assumes that a PCT will come with a reasonable base-case as a default given that there will be a considerable learning curve for most users. As well as changing the house setpoint in response to a signal from the utility, the California PCTs may have the following features:

- Standard connector to wall-plate to eliminate future needs for professional installation.

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[67] Herter, K, Levy, R., Wilson, J. and Rosenfeld, A. 2002. *Rates and Technologies for Mass-Market Demand Response*. Proc. ACEEE 2002, Vol. 5, pp. 161-172. American Council for an Energy Efficient Economy, Washington, DC.

[68] Southern California Edison. 2006. *Draft Report Demand Responsive Control of Air Conditioning via Programmable Communicating Thermostats (PCTs).* Codes and Standards Enhancement Initiative, Public Interest Energy Efficiency Research Program, California Energy Commission, Sacramento, CA. http://www.energy.ca.gov/title24/2008standards/documents/2006-02-22+23_workshop/2006-02-15_PROGRAMBLE_COMM.PDF

[69] Herter, K. 2006. *Eliminating the Need for Rotating Outages through Statewide Air-Conditioning Load Control with Programmable Communicating Thermostats (PCTs).* Personal Communication.

- Ability to receive controls with options for two-way controls.
- Address to include utility, program and geographic area.
- User interface to include system operating mode and bill management events with optional display of pricing and control levels.
- Continuous 1°F load drops during emergency events
- Management of load rebound after events so we don't have all systems turning on at once.

There are several issues still remaining for California PCTs:

- Standardize statewide communication system and activation protocol. Current plans are to make them compatible with some existing wireless home control systems such as Zigbee[70] and Z-wave[71].
- Develop addressability on the levels identified above
- Determine the specific load initiation and recovery strategies to ensure smooth transitions.
- Select the mandatory load reduction strategy: either increase setpoint by a fixed amount (e.g, +2°C (+4°F)) or to a fixed point 26.7°C (80°F)
- Design a standard wall-mount/connection.

A key question with any DR approach is the change in comfort for occupants. A large scale (555 participants) study[72] has shown that DR did not create a comfort problem for most occupants and that participants with higher load savings were not more likely to report discomfort (although there may be an aspect of self-selection at work here, with those who are less sensitive to higher temperatures will tend to be more flexible about reduced air conditioning operation).

The effectiveness of DR also depends on the diversity of the air conditioning load[73] (more details arte given in Appendix B). The diversity arises from system design issues for sizing and other factors such as systems that are turned off. This can be examined by dividing residential Air Conditioning operation on peak into four groups:

A. Off - AC not running during peak.
B. Cycling - AC cycling to meet load and would be responsive to decreased load
C. Could cycle - Continuous operation during peak but would cycle if load decreased
D. On - Continuous operation that would stay on even if load decreased (or system was retrofitted to improve performance).

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[70] www.zigbee.org

[71] www.z-wave.com

[72] Kempton, W., Reynolds, C., Fels, M. and Hull, D. 1992. *Utility control of residential cooling: resident-perceived effects and potential program improvements*. Energy and Buildings, Vol. 18, pp. 201-219. Elsevier Sequoia.

[73] Oak Ridge National Laboratory. 1985. *Field Performance of Residential Thermal Storage Systems, Report EM-4041*. pp. 4-12 to 4-14. EPRI, Palo Alto, CA.

Data from almost 400 systems[74,75,76] in hot-dry western climates (appropriate for application to California) have shown that about 20% of systems are in Category A, 55% in B, 5% in C and 20% in D[77]. This shows that about 60% of systems could respond to a DR signal. In hot humid climates on the peak day about half of the air-conditioners in a ten house sample ran constantly over the 5 to 6 p.m. utility peak[42]. Thermostat operation contributes to these different operating modes. Using daytime setup moves systems from category B to C and D - thus reducing the capacity to respond to a DR signal.

Thermostat operating mode can be similarly broken down into four modes:

1. Constant off
2. Constant thermostat setting
3. Daily setup/down
4. Manual off/on

Research from California and the Southern US indicate that less than 50% of the air conditioners are controlled in mode B[42,78,79,80] and 30% are in category D[76].

A preliminary study of DR in California by San Diego Gas and Electric[81], has shown that these use patterns significantly affected the demand reductions with potential contributors to DR being 32 to 74% of the population on the 12 days that DR was enacted. The main factors contributing to this were:

- In 18% of houses the air conditioner was completely off on peak days
- Allowing user override meant that response decreased as temperatures increased with override use up to 50% on the hottest day.

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[74] Proctor, J., Blasnik, M., and Downey, T. 1995. *Southern California Edison Coachella Valley Duct and HVAC Retrofit Efficiency Improvement Pilot Project.* Proctor Engineering Group. San Rafael, CA.

[75] Blasnik, M., Proctor, J., Downey, J., Sundahl, J. and Peterson, G. 1995. *Assessment of HVAC Installations in New Homes in Nevada Power Company's Service Territory.* Proctor Engineering Group. San Rafael, CA.

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[78] Berkeley Solar Group. 1990. *Occupancy Patterns and Energy Consumption in New California Houses (1984-1988).* California Energy Commission, Sacramento, CA.

[79] Proctor, J. 1991. *Pacific Gas and Electric Appliance Doctor Pilot Project.* Proctor Engineering Group, San Rafael, CA.

[80] Reed, H. 1991. *Physical and Human Behavioral Determinants of Central Air Conditioner Duty Cycles.* Proc. 1991 Energy Program Evaluation Conference. Oak Ridge National Laboratory, Oak Ridge, TN.

[81] Agnew, K., Goldberg, M. and Rubin, R. 2004. *You're Getting Warmer: Impacts of New Approaches to Residential Demand Reduction.* Proc. ACEEE Summer Study 2004, Vol. 2, pp.1-13. American Council for an Energy Efficient Economy, Washington, DC.

- Local weather matters. The choice of DR days was not driven by San Diego weather so that DR days were not necessarily on the days with the greatest possible savings in San Diego.

An earlier (1991-1993) DR study by PG&E[82] used Price Sensitive Thermostats (PST's) that responded to a signal sent by the utility by changing the thermostat in over 90 homes. The PST had an override button that allowed occupants to ignore the setpoint change. Critical Peak Pricing (CPP) was also used to give an incentive to customers to also reduce electricity use of other appliances. The critical price was about eight times the lowest off-peak rate. The CPP was dispatched at PG&E's discretion, but no more than four hours per day and no more than 100 hours per year. The results of this study showed that pre-programming thermostats for higher setpoints had a significant impact on afternoon loads during the high pricing period of 4:00 p.m. to 8:00 p.m. for high use customers, but low-use customers showed little change. Although not discussed in the reference, it is not clear that customer behavior changed for purely economic reasons. The cost of operating a typical 3-ton air conditioner (4kW power consumption) during peak hours was almost $2/hour more than the standard rate. Operating the air conditioning for a two peak hours on a hot day cost less than $4. This premium may be insufficient to change behavior. Interviews with customers also revealed other aspects influencing their response to CPP. For example customers appreciated the ability to monitor and control energy use; enhanced feedback alone may encouraged conservation.

[82] Cruz, R, Keane, D., Sullivan, M. 1994. *Can Dispatchable Pricing Options BE Used to Delay Distribution Investments? Some Empirical Evidence.* ACEEE Summer Study 1994, Vol. 2, pp. 67-76. American Council for an Energy Efficient Economy, Washington, DC.

5.0 Large-Scale Impacts

There is strong evidence that changing thermostat settings can be a successful part of state-wide energy and peak demand management in California.

In 2001 about one-third of Pacific Gas and Electricity's consumers met the state's goal of reducing summer electricity use by 20% (called the 20/20 program) [83]. Changing thermostat settings was the second most popular energy conservation action after turning off unnecessary lighting with about 40% of PG&E customers using this energy savings strategy. In addition about 7% of customers changed thermostats on peak to reduce peak demand. Similar results were observed for customers aware of "Flex Your Power[84]" and PG&E's 1-2-3 Cash Back[85] program.

In January to October 2001 more than 13,000 residential and small business PG&E customers were surveyed to determine their response to the ongoing California energy crisis. The second most commonly reported action (about 75% of respondents) was the reduction in daytime thermostat settings to 68°F and 55°F at night[86]. This indicates that energy savings were primarily in the winter mostly in response to escalating natural gas prices rather than electricity prices or shortages.

During Tokyo's electricity crisis in the summer of 2003, the consumer's response of setting-up air conditioner thermostats proved to be an important factor in reducing overall electrical demand during peak periods.[87]

The use of programmable thermostats is increasing in the U.S. as they are almost always required in new construction (Title 24 being a prime example) and as older thermostats are replaced. For example, in Wisconsin the penetration of programmable thermostats is increasing at about 2.5% per year[11]. This Wisconsin study also found that the presence of a programmable thermostat has a minimal effect on heating energy use due to higher daytime temperature settings.

Energy savings from programmable thermostats are less than estimates because occupants already practice manual setback[88].

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[83] Myers, M., Cavalli, J., James, K., Richardson, V. and McElroy, K. 2002. *Conservation is as easy as 1-2-3: Assessing customer behavior due to PG&E's 1-2-3 cashback information and rebate program.* Proc. ACEEE Summer Study 2002, Vol. 10, pp. 197-208. American Council for an Energy Efficient Economy, Washington, DC.

[84] www.flexyourpower.org

[85] www.pge.com/rebates/123_reduction_plans/

[86] Jennings, C., McNicoll, S., Lawrence, P., Larson, D. and Stone, N. 2002. *Conservation Motivations and Behavior During California's Energy Crisis.* Proc. ACEEE Summer Study 2002, Vol. 8, pp. 129-140. American Council for an Energy Efficient Economy, Washington, DC.

[87] International Energy Agency. 2005. *Saving Electricity in a Hurry.* Paris: International Energy Agency.

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6.0 Design and Operation Issues for Future Thermostats

The issues facing thermostats in the future can be broken down into the following areas:

6.1. Logic

The internal controls logic needs to be capable of dealing with:

- **Defaults**, Defaults make it easier for novice users to implement more complex control strategies. There should be "as shipped" settings that ensure reasonable operation even if an installer, occupant or operator does nothing.
- **Demand Response**. This includes being able to receive (and possibly send) external control signals in order to allow for response to broadcast demand reduction signals.

6.2. Priorities

How does the controller deal with possibly conflicting requirements, such as operation of ventilation systems at the same time as responding to demand reduction signals?

- **Dueling thermostats**. This is observed in large institutional buildings where simultaneous heating and cooling occurs because of settings on multiple thermostats. The most common situation is having on thermostat with a setpoint at a lower temperature than a neighboring thermostat where the difference is greater than the allowable deadband such that one thermostat calls for cooling at the same time as the other calling for heating. As we get more zoned systems and more distributed thermal sensing in homes the possibility for dueling thermostats is increased. Intercommunication between multiple thermostats conditioning the same effective space as well as the use of appropriate deadbands and operator education are all necessary to avoid dueling thermostats.

6.3. Equipment Interface

How will thermostats communicate with other equipment? Depending on how wide we cast our net this issue could be very broad indeed, however the following issues are those most likely to need the most immediate attention:

- **Components.** How will the thermostat communicate with heating, cooling, humidity control, and ventilation equipment. Currently these devices are largely stand-alone but they are becoming more integrated. For example, there are ventilation controllers that use the central furnace blower to distribute fresh air throughout the home and track time of operation for heating and cooling to determine the minimum amount of additional blower operation time required to evenly distribute ventilation air.
- **Time signal acquisition.** To reduce the programming burden on operators and installers the next generation of thermostats should be able to connect (via the internet, cable TV or some other existing time signal) to a time signal generator.
- **Utility (or generically energy supplier for future local/distributed generation).** To allow for utility control - primarily at this time for demand response - there needs to be a way to accept a broadcast signal. This could be by a physical connection (via internet, telephone or power line carrier) or possibly radio.

- **Legacy devices.** Given that thermostats are likely to be replaced without changing heating or cooling equipment, new thermostats need to be able to control this simpler, older equipment. Backwards compatibility will be an essential operating characteristic for widespread use of advanced thermostats and comfort controls.

6.4. User Interface

Standards need to be developed for displays, controls and the user interfaces. Some sort of user interaction uniformity is already necessary and will become more important in the future as controls become more complex. Here are some examples:

- a red light should always mean something bad is happening (e.g., high electricity cost)
- flashing lights should mean failure
- for control levers, hot should always be to the left

There could be standard symbols adopted by the industry for heating, cooling, ventilating, etc.

New displays have virtual buttons, using touch sensitive panels, where an individual area on a panel can take on many control aspects depending on menu selections. This offers the opportunity and probably requirement for greater standardization of display information.

There could also be optional as well as mandatory requirements, such as displaying numerical temperatures or warmer/colder as indictors of setpoint, or displaying consumption information.

User interface standards could be developed via organizations such as IEEE or ASTM. ASHRAE currently has a Research Topic Acceptance Request (RTAR - See appendix A for a current draft) on the subject of building control user interfaces.

6.5. Durability

Controllers need to be resistant to power failure. This includes memory retention so that reprogramming is not needed and re-acquisition of time signals. They also need to be able to adapt and work with changes in occupancy and HVAC (and other) equipment.

6.6. Location

The answer to the questions of "what is a thermostat" and "where is the thermostat" are likely to change. Thermal (and more generally comfort) sensors are likely to be built into devices with other functions. For example, a digital picture frame could double as a thermostat. With thermostats moving from their existing locations typically mounted on walls in hallways, some care needs to be taken to ensure that they correctly sample the space to be conditioned. If a thermal sensor were placed on a windowsill then it would respond to solar effects differently than the rest of the space, and more importantly, it would not have the same thermal environment as the occupants. The opposite of this is to imagine every occupant having their own personal sensor that they carry around with them. This requires some carefully thought out control strategies, for example, what happens if two occupants with very different thermal requirements are in the same zone - who gets priority, or are the two requirements averaged? There is also work underway (at UC Berkeley and the Center for Information Technology Research in the Interest of Society (CITRIS)) to distribute smart sensors (disaggregated thermostats) that communicate with each other as well as the HVAC equipment. They are able to sense their relative locations and use their distributed nature to enable complex zoning and energy conservation strategies.

7.0 Recommendations for Future Research

In surveying both the formal and informal literature on thermostats, in general, we found the topic to be sparsely researched even though the thermostat's influence on energy use can be larger than major technical improvements in heating and cooling equipment or the building envelope (all of which *have* been extensively researched). We identified five areas of research whose results would increase the energy-saving effectiveness of thermostats:

1. Understand how people use and regard thermostats today
2. Improve the effectiveness of user interfaces
3. Develop standards and design specifications
4. Reconsider the role of the thermostat in the context of very low energy homes, zero-energy homes, and "healthy" homes
5. Investigate ways to link public information to more effective thermostat habits

These research areas are described below.

7.1. Understand How People Use and Regard Thermostats Today

We need to learn how thermostats are used today. This research establishes a baseline to ensure that proposed improvements are measurably more effective. These studies would resemble the thermostat surveys undertaken in the UK but would cover more aspects, such as different kinds of heating and cooling systems, impact of age, gender, ability to understand English, etc. The research could also probe what consumers find most frustrating or what they want in future models. Further research should explore the acceptability of adaptive comfort where indoor setpoints are changed depending on occupant response to outdoor conditions. Such information will assist education campaigns to educate consumers to conserve energy. The research will examine how to engage users in the energy efficient operation of their homes using concepts such as: immediacy of response and personalization of interaction.

7.2. Improve the Effectiveness of User Interfaces

The confusing user interface a is major cause of wasteful operating practices. Research needs to identify ergonomic, psychological, and other factors that limit thermostat effectiveness. A key aspect will be to develop test procedures to quantify impacts of new controls, features, or procedures. These tests may take place in controlled settings—a "user interface laboratory"—or as a series of strictly defined evaluation protocols in actual homes. Further tests need to ascertain the influence of gender, age, and command of English on performance. Many procedures and concepts can probably be borrowed from mission-critical activities like flying and anesthesiology.

7.3. Develop Standards and Design Specifications

Additional benefits from effective user interfaces will occur when designs are *consistent* across all models. In this way a user can transfer knowledge and experience gained from one thermostat to another thermostat. (Automobiles, for example, always have the gas pedal on the right and brake to the left.) The standards will cover aspects like consistent use of terms (in English, Spanish, and other languages), symbols, metaphors, and procedures. The standards and design specifications will build on research undertaken in earlier stages. The goal is to avoid situations where two thermostats employ the same term or signal to mean something different. For example, one thermostat informs the user that a heat pump's back-up heater is operating by displaying a green light, while another thermostat displays a red light, and a third displays a flashing red light. Further research would re-examine the role of the thermostat and the feasibility of placing its functionality in other devices rather than leaving it attached to the wall.

7.4. Consider How the Role of the Thermostat changes with different homes

Operation strategies need to be developed for specific housing types and climates. These strategies should include additional sensors for occupancy and outdoor conditions. New standards should also apply to communication between the thermostat and the HVAC equipment, the utility, and perhaps even the mobile phone. These standards and design specifications need to be coordinated with U.S. EPA efforts to redefine EnergyStar thermostats. Homes designed to consume very little energy for heating and cooling present new design challenges for thermostats. Super-insulation and passive architecture, when combined with intermittent occupancy, may lead to longer periods where a floating temperature will be near typical thermostat settings. Recent research suggests that people will be thermally comfortable over a wider range of conditions when they are able to control the temperature. Many new homes—especially in California—may therefore be able to provide satisfactory thermal comfort without operation of the heating or cooling systems. Unfortunately today's thermostats are not capable of accommodating these trends. Parallel research to develop simulation tools to accurately model the thermostat in these conditions is also needed. Older homes (2/3 of California's housing stock was constructed before the first energy code in 1978) with poor insulation and high infiltration, present other challenges.

7.5. Investigate Ways to Link Public Information to Effective Thermostat Habits

Even the best-designed thermostat will be less effective if the user's mental model of the heating and cooling systems is flawed. For that reason, we need to learn more about the misconceptions (such as the notion that set-backs don't save energy because they require extra energy to restore the home to the original temperature). This information will help policymakers develop more effective information and education campaigns and help manufacturers design more effective instruction guides.

8.0 Conclusions

Modern thermostats are a convenient way to maintain or improve thermal comfort and almost certainly save energy and peak demand in situations with highly regular and predictable occupancy patterns. Over the whole population, however, the savings are much smaller and modern programmable thermostats may even lead to higher energy use. Large portions of the population, including households operating on irregular schedules, the elderly, or those unable to read English, may be excluded from easily achieving these savings. Problems with modern thermostats include installation incompatibilities and controls that are difficult to understand or modify. The meaning of many terms, symbols, and actions are inconsistent from one model to another, which limits consumers' ability to apply knowledge from one model to another. Surprisingly little research has been undertaken to assess the effectiveness of different user interfaces for thermostats, however, conventions and paradigms from other industries could be transferred.

Thermostats have enjoyed gradual improvements in technical sophistication over the last century. This relatively sedate pace of improvements is almost certain to change. New responsibilities, such as coping with more complex heating and cooling systems, ensuring acceptable indoor air quality and responding to fluctuating electricity prices cannot be accommodated even with today's most intelligent thermostats. The goals of zero-energy homes add other layers of complexity, such as accounting for on-site generation. Above all, the identifying feature of the next generation of thermostats will be communication with many different devices. The future thermostat will cease being an appendage to the heating and cooling systems and become an independent device of its own, sensing and communicating with a wide range of devices.

The ability of a heating and cooling system to more closely "personalize" a space conditioning strategy likewise increases the importance in the way in which occupants operate the thermostat. The thermostat's interface with the user needs to be completely overhauled in order to accommodate widely varying lifestyles, the elderly, and those who understand little English. The role of behavior with respect to energy consumption has been almost neglected yet, as indicated above, positive behavior will be a necessary element of future thermostat designs and low-energy lifestyles.

9.0 Appendix A. ASHRAE RTAR 1502. User Interface Design for Advanced System Operation

TC/TG: TC 1.4 Control Theory & Application

State-of-the-Art (Background):
Many EMCS user interfaces do not readily show information necessary for advanced operation of a commercial building. Training users is a process that requires an initial session, followed by repeated training sessions [6]. This level of effort is hard to implement and maintain. System performance deteriorates from lack of timely monitoring and intervention [1], [2,],[3], [4]. EMCS user interfaces typically do not display executive level information such as normalized building energy use by area or by system type, system code compliance (example: ventilation) or comfort indices so that key decision makers can intervene when performance falls below targets. [4], [5], [7], [8], [10]

Advancement to the State-of-the-Art:
To improve the efficiency of buildings, an advanced building display is needed that involves the building engineering and maintenance staff as well as executive level decision makers, shows actionable items, and provides feedback on the overall state of building operation. Such a user interface should be highly intuitive to allow operators to take action while eliminating expensive training sessions. Examples of universally understood user interfaces in everyday life are vehicle dashboards, radios, alarm clocks, video-game controllers, and the controls of the iPod®. The dashboard should communicate the operating state of the building on one or two screens.

Justification and Value to ASHRAE:
This project will provide the information designers need to specify effective user interfaces for managing building operation. Such user interfaces will allow building operators to take action to correct problems and to verify that systems operate at target efficiency and effectiveness. Potential benefits are:

- System functions no longer disabled (system runs in “auto”, not in “hand”)
- Higher building energy efficiency
- Better equipment maintenance
- Higher building comfort
- Higher building portfolio value
- Consistent with goals of sustainability and continuous commissioning by providing real time feedback to operator

Objective:
To determine what information and system feedback the building engineering community is looking for, and to translate this into broad recommendations for performance specifications to support the engineering design, building operations and EMCS manufacturing communities.

1. Determine when and how control system interfaces are used in operating buildings today, through interviews of building operators, identifying their job responsibilities, objectives, typical daily operating modes, reporting structure, and comfort with computer interfaces.
2. Determine current state (functions, capabilities) of market-leading EMCS interfaces.
3. Determine market acceptance through operator surveys (what functions and capabilities are often used, what functions are never used?)
4. Determine market wishes through operator interviews; provide examples of what might ideally be implemented and get opinions (Which of the interfaces would you like to see, why, what else would you like to see)
5. Formulate recommended performance specifications for use by design engineers and EMCS manufacturers or as basis for industry guidelines.

Specific areas of focus for interface development:
Selection of building metrics that may be displayed on the dashboard for the benefit of building operators, managers and/or occupants. Parameters might include, but not be limited to:

1. Energy feedback

a. Currently lacking from most standard interfaces are easily readable metrics such as kW/ton for central plants, MBH/sqft, kW/sqft and the like, as well as easily readable metrics for historical overview against similar buildings [11],[12],[13],[14] and / or the buildings own energy baseline [15], [18]

b. Clear indications when building performance is below target (energy use "green" vs energy use "red" in very simple, overall terms). Some tools showing this kind of data should be available by spring of 2008 [9], and could be linked to an EMCS interface directly, others are in early development [19].

2. Comfort Feedback

a. Provide information about the overall comfort index of the building based on temperature, humidity, ventilation (CO_2)

b. Potentially provide annualized overall survey such as CBE online building survey [16]

3. Alarms:

a. Equipment, level, temperature, filter pressure and similar alarms can typically be configured to arrive at the operator terminal or phone. In practice, one of three problem scenarios occur:

  i. Lack of alarms - insufficient configuration, alarm points in factory default settings

  ii. Daily or hourly string of alarms - all alarms are enabled at same level of importance

  iii. There is no way to manage multiple alarms (for example, to detect that a particular alarm is triggered every day at the same time, quickly determine how long an alarm has been happening, or readily identify a "new" alarm.

b. Alarm messages are not tailored to operator needs - "Alarm – Filter" or similar messages may be found on many installations. They let the operator know something is wrong, but don't provide enough information to allow directed action. What filter is in alarm? Where? What is wrong – presumably high differential pressure?

4. Schedules

a. Creative interface approaches exist that allow scheduling for holidays, weekends, monthly and seasonal effects. Despite this, studies show that schedules are not maintained and buildings often remain in their occupied state when this is not required.

5. Help:

Rather than issuing alarms only, issue alarms in conjunction with suggested resolutions and remedial actions that can be taken by operator. This might be similar to the F1 key in the Windows operating system.

6. Trends:

Most EMCS platforms allow trending. The main use for this function is to provide benefits for the operator, namely to facilitate troubleshooting and to allow monitoring. Instead, many operators are reluctant to use trend features because:

  i. Trends are too complicated to set up and perceived as requiring too much disk space, raising fears that they will crash the system.

  ii. Network bandwidth problems and expected communication errors caused by "excessive" trend use are also reasons for building operators to leave trend features unused.

7. Key Building data should be accessible through the dashboard.

This includes floor plans, commissioning documents (tests, commissioning plan), energy models, specifications, sequence of operations, submittals, O&Ms and all other data compiled during the design and construction. Access could be in the form of a button on the interface that opens a pdf with relevant information, or any other simple retrieval method that allows copy/paste operations or "save as" operations to other programs or data formats. For CAD files, a compressed version of original files could be saved along with quick-access pdf's. This access to design information does not really add a function to the EMCS but merely enables a link to another file. However, it ensures that all building data (design and operations) are kept in one place for easy access to both the building owners and providers of 3rd party statistics, research or analysis.

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10.0 Appendix B. Diversity effects on DR

A system can only make an impact on DR if it is operating at peak, therefore system design and sizing with respect to the load at peak times is critical. Diversity in air conditioner operation did reduce the effectiveness of the DR program in a study by Kempton et al. (1992). Diversity includes the effects of different loads (arising from changes in weather and construction) in different houses as well as equipment capacity. The ratio of building load to equipment capacity determines the duty cycle, i.e., the fraction of time that the equipment has to operate to meet the load. The duty cycle length changes the effectiveness of different demand control strategies. About 16% of houses had duty cycles below 0.50 on peak days so a 50% dynamic load controller did not reduce air conditioner operation for these homes. About 60% of the houses had duty cycles less than 0.75 resulting in no savings for a 25% off time dynamic load control and half the expected savings for a 50% off time control.

A study at Oak Ridge National Laboratory (1985) from more than 20 years ago showed that the average duty cycle was in the range of 0.5 to 0.6. The load savings were found to correlate with peak duty cycle. The effect of duty cycle was sufficient to completely remove any correlation between load savings and indoor temperature increase. This suggests that DR controllers should avoid a fixed duty cycle or a duty cycling strategy. However, if a duty cycle strategy is used, the length of the duty cycle should either be based on a pre-DR screening or the DR controller should adjust the duty cycle when responding to a DR signal based on a duty cycle without the DR signal present. California DR programs need more detailed information on duty cycles on peak days across the state to obtain more accurate estimates of load savings and minimize discomfort to occupants.

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11.0 Appendix C. Indoor Air Quality Ventilation & Energy Conservation in Buildings Conference Paper: EMERGING REQUIREMENTS FOR RESIDENTIAL THERMOSTATS IN NORTH AMERICA

Reference:
Meier, A. and Walker, I. (2007). "Emerging Requirements for Residential Thermostats in North America". Proc. Indoor Air Quality Ventilation & Energy Conservation in Buildings 2007, Sendai, Japan.

EMERGING REQUIREMENTS FOR

RESIDENTIAL THERMOSTATS IN NORTH AMERICA

Alan Meier* [1] and Iain Walker [1]

[1] *Lawrence Berkeley National Laboratory, Berkeley, USA*

ABSTRACT
The requirements for thermostats are increasing in the U.S. for a combination of reasons. Firstly, energy conservation and Demand Response programs are requiring thermostats to have more complex controls that can communicate with electric utilities. Other pressures are caused by the increasing sophistication in U.S. homes such as systems for mechanical ventilation, economizers and ventilation cooling that interact with operation of heating and cooling systems via thermostat controls. In order to meet these challenges, U.S. thermostat manufacturers and regulators are focusing on improving user interfaces, developing standardized communication protocols and meeting the requirements of pending legislation

KEYWORDS
Thermostats, energy conservation, California, regulations

INTRODUCTION
The thermostat converts occupant thermal comfort preferences into operations by heating and cooling systems in modern homes. Thermostats have gradually evolved to match the increasing sophistication of the heating and cooling systems that they control. Early models in North America were simple electromechanical devices matched to forced-air systems (which are the most common systems in North America). Modern thermostats often contain microprocessors and allow the occupant to set desired maximum and minimum temperatures according to a pre-arranged schedule. Other features include operating in a ventilation mode (as opposed to heating or cooling), de-humidification, and controlling multi-stage operation of heat pumps. These

* Corresponding author. Tel +1 (510) 486-4740 akmeier@lbl.gov

options allow consumers to minimize heating and cooling costs while maintaining acceptable thermal comfort.[89]

Recent changes in building codes and elsewhere will require thermostats with more capabilities. This paper outlines these developments and speculates about the long-run implications.

CHANGES IN ENERGY STAR SPECIFICATIONS FOR PROGRAMMABLE THERMOSTATS

In 1995, the Energy Star program (Energy Star 2007) established specifications for programmable thermostats. A Programmable Thermostat enables the user to establish a schedule with different temperatures. Energy Star recognized that a programmable thermostat could greatly reduce heating and cooling costs by lowering (or, during the summer, raising) indoor temperatures when occupants were away or slept. Computer simulations and actual measurements demonstrated that a correctly programmed thermostat could often save 15% or more from heating and cooling bills. Manufacturers and retailers offering thermostats meeting the Energy Star specifications were allowed to use Energy Star endorsement materials and benefited from an aggressive public relations campaign run by the Energy Star program.

In 2006, however, Energy Star terminated the original program endorsement program and replaced it with a much weaker consumer information program (Energy Star 2007). Its decision was based on a growing body of evidence that programmable thermostats did not deliver the expected energy savings and possibly increased use of heating and cooling energy in many homes. In some studies, homes equipped with programmable thermostats consumed more energy than those homes relying on manual thermostats. Energy Star (and the authors of the individual studies) offered several explanations for these counterintuitive results. One key reason is that many people were already using manual thermostat schedules that mimicked the automatic schedules used in the Energy Star thermostats. It was also speculated that many occupants never learned to correctly program the thermostats in the first place. Other consumers over-rode the thermostat's automatic features and operated them like a switch (e.g., off and on) and in other cases, the programmable thermostat was simply less effective than constant vigilance by the occupants. These studies as a group strongly suggested that programmable thermostats increased energy use but they were not designed to determine how much energy would have been used without the programmable thermostats or that self-selection had occurred. A recent study (RLW Analytics 2007) that focused on a heating dominated climate (New Jersey) and included a much larger sample of several thousand homes concluded that programmable thermostats saved about 6%. This final study suggested that climatic variability was responsible for the different results. It further suggested that the Energy Star thermostat savings estimates could be valid in more extreme climates, but overestimate the savings for mild climates.
After terminating the program, Energy Star left open the possibility of restoring the endorsement program for programmable thermostats. However, the manufacturers would still need to offer improved technologies, interfaces, and field verification that the improved thermostats will reliably save energy compared to manual operation. A new Energy Star thermostat (if approved)

[89] Nevertheless, few American thermostats match the complexity or sophistication of thermostats used today in Japanese-style mini-split heat pumps. One explanation is that fewer options are feasible when heating and cooling centrally.

would almost certainly need to conform to new requirements imposed by building codes and electric utilities. These requirements are discussed below.

NEW VENTILATION REQUIREMENTS IN CALIFORNIA'S BUILDING CODE

In 2008, California's building energy code—often referred to as Title 24 (CEC 2007)--will require mechanical ventilation systems in all new homes. This measure was taken to ensure that adequate indoor air quality would be maintained without reliance on natural air infiltration. Sweden, Canada, and Japan, already require mechanical ventilation but systems in U.S. do not. This is mostly because historically homes in the U.S. were very leaky and it was considered that natural infiltration provided sufficient ventilation. However, new construction in the U.S. is becoming tighter and the need for mechanical (or reliable passive) ventilation is increasing - particularly in energy efficient housing (Sherman and McWilliams 2005).

Several ventilation technologies will be used in California. The first uses continuously operating exhaust fans in bathrooms. This approach is already widely used in Europe. The second technology operates the exhaust fan on a timer so as to avoid operation at times of peak heating or cooling ventilation load. This timed operation system could be controlled by the clock in the thermostat. A third technology intermittently supplies fresh air through the forced-air heating and cooling system. The latter system is controlled by, or be coordinated with, the thermostat through a fan cycling control and motorized damper.

Other parts of the United States and Canada will probably implement similar requirements after California so the demand for effective controls will soon be larger than just California. Modern thermostats capable of reliably controlling ventilation are now becoming available in the U.S., such as the intermittent supply air system described above and residential ventilation cooling and economizer systems that deliberately use outdoor air to provide space conditioning.

DEMAND RESPONSE AND COMMUNICATING THERMOSTATS

After California's 2001 electricity crisis, the state made control and reduction of peak electrical demand a priority. The policies consisted of both mandatory and economic measures. The mandatory measures included revisions of the state building energy code in 2005. The new code required numerous design changes aimed to buildings' reduce peak electricity demand (as opposed to simply conserve energy).

Other measures give consumers economic incentives to avoid consuming electricity during periods of peak demand. This approach is often called "Demand Response". An important element of Demand Response is to adjust the price of electricity based on the cost of providing it. During periods of peak demand the price of electricity will rise sharply, sometimes to over ten times the base rate. Demand Response leaves consumers the option to not respond but they will be required to pay very high electricity prices. California hopes to control about 5% of peak demand through Demand Response (Herter et al. 2002). Note that Demand Response programs differ from Demand *Control* programs. Demand Control programs take over control of the consumers' equipment (typically by periodically switching them off or changing thermostat setpoints) during critical periods.

Air conditioning is the largest contributor to peak power demand in much of the U.S., so most Demand Response programs seek to reduce air conditioning electricity use in residential and commercial buildings. One of California's Demand Response programs will require the installation of thermostats capable of receiving price signals and adjusting the temperature in response (CASE 2006). The "Programmable Communicating Thermostat" (or PCT) specification

will be proposed for adoption in January 2008 and, if adopted, will be required in new homes after April 2009.
The PCT is unique in that it will be capable of receiving different kinds of signals from the utility. During normal conditions, the utility will broadcast electricity price signals but, in case of a grid emergency, it can also send control signals. The thermostat will respond to the price signals by raising indoor temperature (if programmed to do so). One important feature of the PCT will be standardized communication protocols which will permit interoperability among systems. These signals may be radio frequency broadcasts, available through the internet, or possibly via the electricity distribution network (the wires connected to the house). The communications protocols for the PCT are still under development and must address important issues related to security and one-way addressing. Nevertheless, manufacturers are already designing thermostats to comply with expected specifications and at least one prototype is available.

DISCUSSION

In addition to the normal pressures to offer new features, the examples above demonstrate that other issues are strongly influencing the design of future thermostats. On one side new responsibilities are being added to thermostats (e.g., ventilation control and Demand Response) which add to the device's complexity. At the same time, Energy Star is retreating from specifications because it found that current levels of complexity may have contributed to lack of savings. Issues of complexity also depend on who is installing and/or programming the thermostat: either the building occupants or a contractor/installer. Incidentally, it is not clear which of these two groups is necessarily more sophisticated and better able to master more complex controls. Energy Star has to date not considered specifications for thermostats that would include capabilities to address ventilation and peak power demand.

These specifications need to be coordinated to so as to ensure that the desired results are achieved. In some cases priorities must be established. For example, should mechanical ventilation be suspended during periods of peak demand? Put another way, should ventilation take precedence over peak power demand? Indoor air quality standards suggest that short term interruptions of ventilation for a few hours are acceptable from a long-term exposure point of view. However, if we want to retain the ability to eliminate chronic short term pollutants then some sort of ventilation override is required. This ability to reduce ventilation load under peak conditions can save energy and, more importantly, have a significant reduction in peak building load (a key concern for Demand Response programs).. In some areas, the air quality during periods of peak electrical afternoon (typically very hot afternoons) may be worse outside than inside (e.g., ozone in Southern California).
The Energy Star experience suggests that the user interface to thermostats needs to be improved. There has been almost no research on user comprehension of existing displays, symbols, controls. Adding new features will further complicated the user interface and the likelihood that users select incorrect settings. Certain aspects may need to be standardized. A standardized user interface for power management of computers and related equipment has already been adopted by IEEE and supported by Energy Star. The standardization requires that manufacturers use certain symbols, terms, and actions identical across all products. A similar standardization of user interface may be needed for thermostats if we want to improve the likelihood of contractors correctly installing controllers. Standardization may also help consumers who install their own

thermostats, but this is likely to be less of an effect than for contractors because consumers will very rarely install a thermostat.

The examples above also demonstrate the growing number of products whose operation is either controlled or needs to be monitored by the thermostat. Here, too, standardized protocols for communication will be increasingly important. Some progress has already been made although the protocols are often proprietary and hinder interoperability.

The thermostat has traditionally been a component of the heating and cooling systems. However, advances in consumer electronics, communications, and product design may cause thermostats to become separate from the heating and cooling systems.   Future thermostats may reside in PCs, digital picture frames, or other kinds of remote controls. This evolutionary step must wait until communication protocols are standardized.

CONCLUSIONS

The thermostat plays a key role in assuring thermal comfort and indoor air quality in homes. New codes, incentives, and technologies will stimulate important changes in the residential thermostat in North America. The principal drivers in the U.S. are revised building codes (particularly in California), which require mandatory ventilation and raising temperatures during summer electricity shortages. Response to electricity shortages will require a degree of communication between utilities and homes never before undertaken in the United States.

By withdrawing its endorsement of programmable thermostats, the Energy Star program has challenged manufacturers to develop new thermostat designs that will more reliably save energy. This may require entirely new user interfaces and a greater understanding of how consumers actually select a level of thermal comfort.

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