Residential Thermostats: Comfort Controls in California Homes

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Literature Review

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).

A Brief 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 keep the air flow and temperature correct. Only the wealthiest could afford the staff (usually slaves) required to maintain the fire in a private residence.

Cornelius van Drebbel (born in 1572 in Alkmaar, Holland) is commonly credited[2] 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[3]: "… 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[4]) 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.

At almost the same time (1885) Albert Butz, who developed a furnace regulator that used a flap to control air entry (and thus heat output) to a furnace[5]. His company (the Electric Heat Regulator Co.) eventually became Honeywell.

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

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

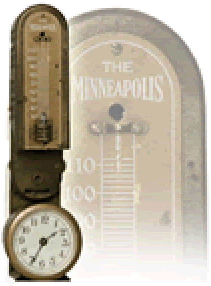
[3] Mencken, H.L. 1931. *The Boons of Civilization* (from the American Mercury, January 1931, pp. 33-35).

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

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

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.

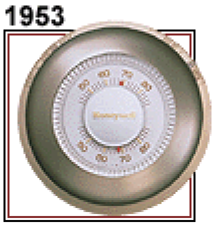


First Programmable Thermostat

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.

followed ten years later by the first electric clock thermostat[6].

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.



T-86 "Round" Thermostat

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

In1968 Honeywell produced the first combined temperature and humidity control device, in a somewhat less iconic shape!

Combined temperature and humidity control

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 proposed external control for demand response in California while others relate to 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.

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[7] 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°) 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 tool 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[8] 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[9] 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[10] found that self-reported thermostat data was a better indictor 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[11] found average setbacks of 3.3°C (5.9°F) for approximately eight hours a day.

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[12] 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.

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[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] 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.

[12] 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.

In a more detailed examination of room-to-room temperature variability in 1000 British homes[13], 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[14] (or similar) there is the assumption of a constant setpoint of 24°C (75°F) for cooling. In humid climates there is evidence[15] that this may be too high 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[16] indicated that typical operation is at 26.5°C (80°F). This is reflected in the assumed setpoints in Title 24. 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%[17]. A CEC/PIER Codes and Standards Enhancement Study[58] 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

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[13] 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.

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

[15] 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.

[16] 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.

[17] 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.

about 0.3°C (0.6°F) compared to 1.4°C (2.5°F) for standard bimetallic thermostats[18]. 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[19]. It was found that occupants manipulated automatic thermostats less than manual thermostats.

An investigation of historical thermostat settings based on those reported in the RECS[20] database has shown that winter temperatures have a gradual increasing trend (of 0.5°C (1°F) to 0.75°C (1.5°F)) with time from 1984 to 2001[21]. 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).

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[18] 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.

[19] 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.

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

[21] 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.

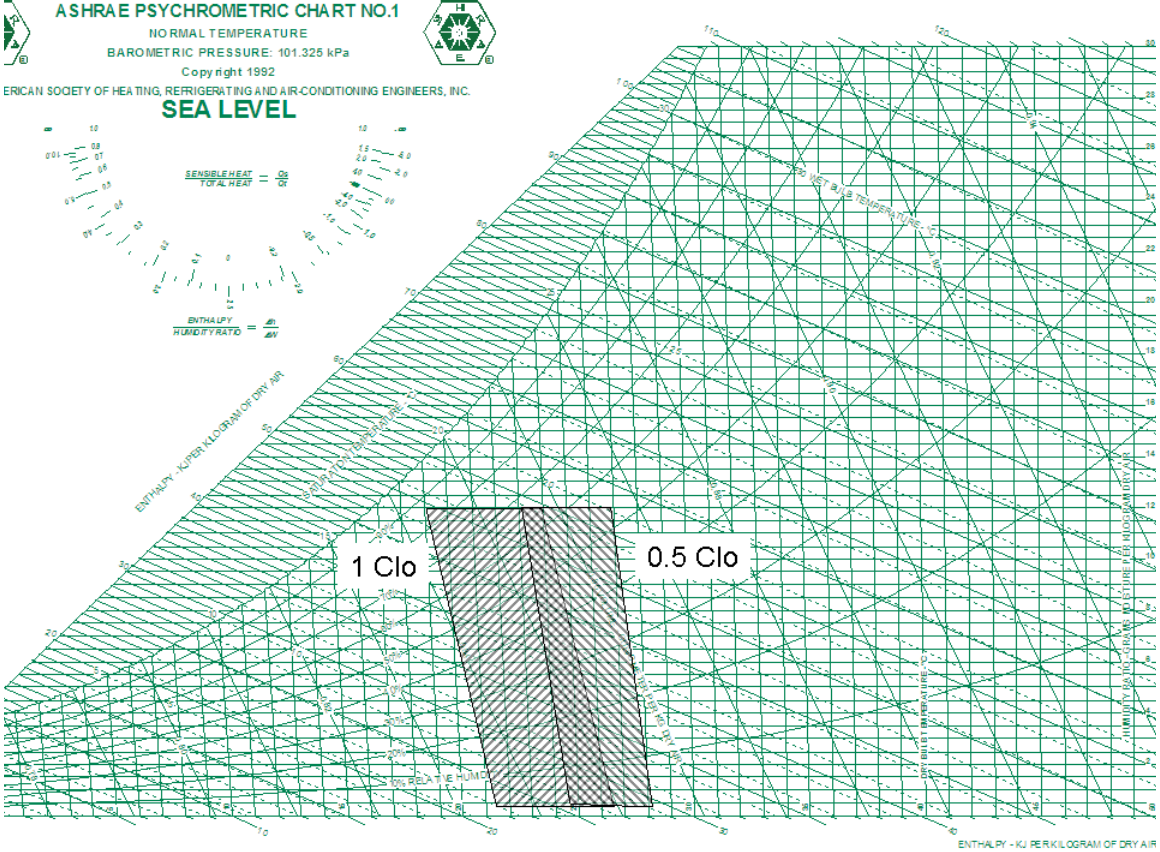
Changing Temperatures

Perception of thermal comfort can depend not just on the current temperature, but also the rate of change if temperature. A literature review[22] of thermal comfort stated that there is good experimental evidence that if temperatures change a 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[23] 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[24].



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[22] 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.

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

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

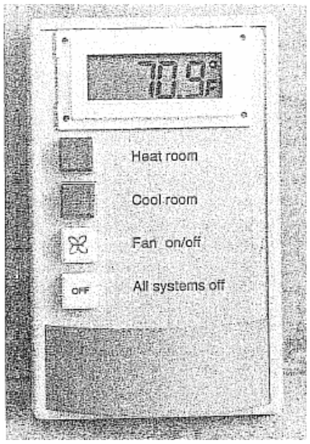
ASHRAE Standard 55 comfort zones for two clothing levels

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[25] 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[26] - 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

Advanced Thermostat Controls

In Japan heating, cooling and ventilating controls are more sophisticated than we are used to in North America[27]. 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

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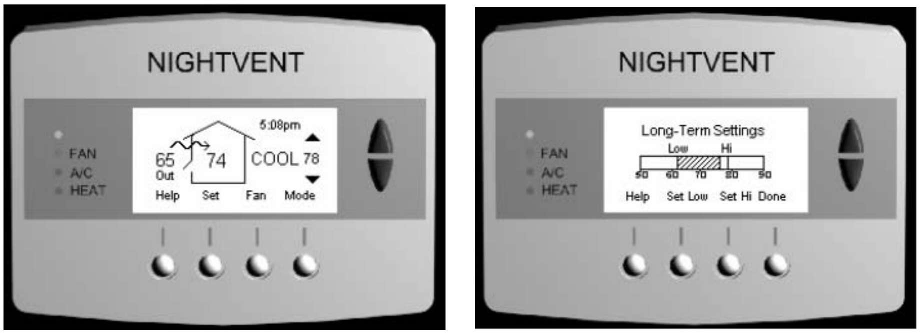
[25] Keyson, D.V., de Hoogh, M.P.A.J., Freudenthal, A. and Vermeeren, A.P.O.S. 2000. *The Intelligent Thermostat: A Mixed-Initiative User Interface*. Proc. CHI 2000 Conference on Human Factors in Computing Systems. Association for Computing Machinery.

[26] 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.

[27] 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.

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 mimic 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 user uses 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-recorded protocols relating to this perception of thermal comfort that change depending on the room. The differences between these performance characteristics and typical North American systems is due in some part to cultural differences. Although the controls in Japan are more sophisticated, it does not imply that occupants are. In a survey[27] of 20 Japanese residents using these systems a majority reported that they did not understand or use all the available control options.

For ventilation cooling controls an advanced controller has been developed in California (NIGHTVENT)[28] 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”.



Display screens for NIGHTVENT

Thermostats that had an integrated light sensor were evaluated in 23 electric baseboard heated homes in New England[29]. 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.

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[28] 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.

[29] 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.

For heat pumps, the use of setback is generally not recommended because the recovery from setback requires additional capacity that in heating mode is provided by lower efficiency electric resistance heat[30]. This also presents greater peak demand on winter mornings - although this is of less concern in California due to low market share of heat pumps. This effect can be reduced by using adaptive recovery thermostats that slowly increase thermostat settings allowing heat pumps to avoid electric resistance heating.

In commercial buildings current research is looking at the use of each occupants computer as an interface between individuals and the building energy management system. Sophisticated software using autonomous agents is used to optimize system operation - introducing concepts such as the “caring building”[31]. It is not clear how this will translate into residential buildings where we do not have occupants sitting at desks in front of computers (although this is happening more and more - particularly at my house!).

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[30] 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.

[31] 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)

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. Mercury switch electromechanical thermostats are inexpensive ($20-$30) and their simplicity can be attractive to contractors and users. Electronic programmable thermostats have a greater range and cost about $30 to $150 depending on brand and features[32]. There is some overlap with the most expensive mercury switches costing about the same as an inexpensive electronic programmable thermostat. This indicates that it is possible to increase features without necessarily increasing price. However it seems likely that as more features, controls, and sensors are introduced the cost will increase. These cost increases will have to be weighed by consumers against the increase in services. 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., EnergyStar 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.

This issue will be further clouded in the future is thermal comfort control just becomes one feature of a complete whole-house integrated control system (that includes ventilation, HVAC operation, lighting, window shading, interactions with other appliances) or is integrated into personal electronic devices that we carry around (like cellphones). This considerably complicates the economic decisions on the cost of thermal comfort controls, possibly to the point where it becomes irrelevant. This path has been taken to extremes in some studies that have, at least at a prototype level, linked HVAC operation with most other appliances in the home, home security systems, lighting, etc[33]. Although it seems that the sophistication and knowledge required of the user would pre-empt this level of integration in most homes.

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

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

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. 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" vs. The "feedback" theory of meeting 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[34,19].

In a related issue, studies on the use of Energy Star setback thermostats have shown that the predicted energy savings are often not found because the users that utilize the programmable setback are the ones that manually setback their manual thermostats[35]. Although this does not imply that people who setback manual thermostats were using the valve theory it does show that providing new technology may not actually change energy use or comfort because users were able to make existing/old technology provide the same comfort and energy use. However; a more recent larger scale (about 7000 households) billing analysis study[36] 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.

A difficult issue with thermal comfort is the variability from person-to-person of the appropriate conditions for thermal comfort. This is not just a household-to-household variability. It is often the case that occupants of the same house have different desired temperature settings. In a Florida study[37] it was found 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 cooling energy used in 10 identically constructed homes in this Florida study. The studies authors concluded that this may be a reason to oversize the air conditioning equipment compared to industry standard ACCA Manual J and S calculations because the contractor will 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 development of goal setting strategies for occupant interactions with the thermostat to reduce these effects[38].

A large scale (3094 participants aged 15-74) study in Finland[39] showed significant differences in thermal comfort, temperature preference and thermostat use between genders. "Females are

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

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

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

[37] 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.

[38] 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.

[39] 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.

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 tend to arise because the occupants do not know how to use them successfully (with the emphasis on *successfully*)[40] or there are ambiguous lights or symbols that confuse the user or lead them to do the opposite of what they want. Here are a couple of examples from heat pump controls:

- The indicator lights on some heat pumps 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[41] as guidance for future work on interfaces:

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

When occupants are not happy 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[42].

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[43].

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

[41] 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.

[42] 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.

[43] 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[10] resulted in 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.
- Setting 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[44] 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[45] found that “Apparently, 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 to 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.

A study of energy use among low-income elderly people in California[46][47] raised the issue that this segment of the population has different attitudes and priorities. Although difficult to disaggregate the age effects from the low-income effects, this study was able to identify some key issues. Several occupants never touched the thermostat - allowing relatives or building management to set the temperature. The reasons for this included a fear of doing the wrong thing (i.e., they did not feel like they had enough knowledge to set the thermostat but they were willing to do something if they knew what to do), different sensitivity to temperature extremes, and the use of auxiliary heating and cooling (either with room heaters or the use of the gas stove - the latter of which led to humidity and potential health problems for some occupants). Thermostat settings were 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 (for some occupants, there energy bills were more then their rent). Thirty percent of residents reported having trouble with the thermostat and the study authors thought it was likely that the true fraction was even higher due to occupants using the thermostats incorrectly without knowing it. The problem was in two parts- the labeling of the thermostat was in small letters that were hard to read for the elderly occupants. Secondly, the design of the 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. The tendency was for

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[44] 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.

[45] 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.

[46] 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.

[47] 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.

occupants who wanted heat to move 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[48] 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.

Room air conditioners

In this study, room air conditioners are self-contained units that are commonly installed in windows. Therefore, this does not include mini-split systems. Mini-split systems are currently extremely rare in residential buildings in the US and therefore there is little information available on their performance. However interest is increasing for these systems, and they will require consideration as we look to the future.

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[49] 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

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[48] 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.

[49] 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.

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 left the unit turned on and allowed the temperature setting 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).

Hydronic Controls

Hydronic systems generally tend to have longer response times than forced air systems and therefore may benefit from the use of more advanced control strategies[50]. 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.

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[50] 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.

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" [51], also known as Title24. Appliances (including furnaces and air conditioners) are regulated by: "California Code of Regulations, Title 20, Appliance Efficiency Regulations"[52], 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[53] 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[54] (ACM) has tabulated standard values for setback thermostat settings as shown in Table 1. Additional values are given for living and sleeping zones for zones systems. The switch from heating to cooling is determined from a seven day running average out door temperature. When this running average is less than or equal to 60°F then the building is in heating mode and if greater than 60°F the building is on cooling mode.

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[51] 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.

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

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

[54] 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 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[55] assume constant setpoints, however, the ACCA sizing manual[56] does allow for excess capacity to be installed.

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

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

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[57]:

- Potential demand reductions are large - 20% (10 GW)
- Residential customers prefer AC curtailment to other options
- 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 [58] 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 for all of California
- Retail purchase - consumer owned, operated and maintained

A summary of the PCT vision for California[59] 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 will not be overrideable 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.
- 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
- Develop addressability on the levels identified above

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[57] 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.

[58] 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

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

- 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[60] 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).

Diversity in air conditioner operation did reduce the effectiveness of the DR program. Diversity includes the effects of different loads (due 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. This is important because it changes the effectiveness of different demand control strategies. 16% of houses had duty cycles below 0.50 on peak days so a 50% dynamic load controller did not reduce air conditioner operation. 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. Expanding this issue nationally an older study[61] found 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 not have a fixed duty cycle or not use a duty cycling strategy. If a duct cycle strategy is used, the duty cycle should either be set based on a pre-DR screening or that the DR controller change the duty cycle when responding to a DR signal depending on the duty cycle without the DR signal. In addition, it was suggested that rather than sense site temperature that the DR signal be broadcast - this is the path currently proposed for California DR. A key question for California DR programs is to get better information on duty cycles on peak days across the state, for individual utilities and on more local levels (possibly down individual sub-stations).

The efficacy of DR programs will depend on the diversity of residential Air Conditioning operation. 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).

Data from almost 400 systems[62,63,64] 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%

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[60] 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 equoia.

[61] 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.

[62] 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.

[63] 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.

[64] Blasnik, M., Downey, J., Proctor, J., and Peterson, G. 1996. *Assessment of HVAC Installations in New Homes in APS Service Territory.* Proctor Engineering Group. San Rafael, CA.

in D[65]. 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[37]. 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:

A. Constant off
B. Constant thermostat setting
C. Daily setup/down
D. Manual off/on

Research from California and the Southern US indicate that less than 50% of air conditioners are controlled in mode B[37,66,,67,68] and 30% are in category D[64].

A preliminary study of DR in California by San Diego Gas and Electric[69], 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.
- 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[70] 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 effect 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 For a typical 3 ton air conditioner (4kW power consumption) the cost to run the air conditioning on peak was $1.94/hour more than the standard rate. So to operate the air conditioning for a couple of peak hours on a hot day cost less than $4. It is questionable that this is sufficient to change behavior. In addition, customer interviews did reveal other issues

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[65] Peterson, G., and Proctor, J. 1998. *Effects of Occupant Control, System Parameters and Program Measures on Residential Air Conditioner Loads.* Proc. ACEEE 1998, Vol. 1, pp. 253-264. American Council for an Energy Efficient Economy, Washington, DC.

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

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

[68] 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.

[69] 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.

[70] 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.

influencing the response to CPP: there was the perception of the possibility of achieving cost savings and that users appreciated the ability to monitor and control energy use. In other words the enabling aspect of the technology was important in adoption by customers as well as perceived economic reasons.

The Future

Some researchers have investigated some very complex home automation systems[33] and certainly the technology and software exist to create systems that are integrated with the electricity 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[499].

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[71].

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[71] 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.

Application Issues for Public Policy

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) [72]. 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[73]" and PG&E's 1-2-3 Cash Back[74] 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[75]. This indicates that energy savings were primarily in the winter mostly due to escalating natural gas prices rather than electricity process or shortages.

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 it is estimated that the market saturation of programmable thermostats is increasing at about 2.5% per year[10]. 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[76].

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[72] 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.

[73] www.flexyourpower.org

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

[75] 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.

[76] Cross, D. and Judd, D. 1997. *Automatic Setback Thermostats: Measure Persistence and Customer Behavior.* The Future of Energy Markets: Evaluation in a Changing Environment, Proc. 1997 International Energy Program Evaluation Conference, Chicago, IL.

Design and Operation Issues for Future Thermostats

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

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.
- **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.

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.

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.

Durability

Controllers need to be resistance to power failure. This includes memory retention so that reprogramming is not needed and re-acquisition of time signals.

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 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.

Research Issues

The following key issues have been identified that require additional research if we want to answer questions about what changes need to be made in Title 24 to better reflect actual home operation:

- What thermostats are currently being sold and what is the market share in various categories: manual, mercury/electronic, programmable, communicating, other advanced features (e.g., economizer and ventilation controls)?
- What are the typical values and range of setpoints and indoor temperatures in California homes?
- How do these typical values and ranges change on peak?
- How do they change with climate and geographic location?
- How can we make thermostats easier to use (interface and operation issues)?
- How effective are smart thermostats at learning occupant behavior?
- How important are override settings to occupants?
- What features do occupants want that are currently not offered (e.g., timers on room air conditioners)?
- How will mechanical ventilation rates and equipment operation change thermostats?
- Does feedback to occupants matter?
- How will thermostats interact with whole house monitoring systems?

The proposed approach being taken in California for DR is supported by the information in the literature review.

For Demand Response to be an effective program that significantly impacts peak loads the following questions need to be answered:

- How many systems can respond to a broadcast control signal? The peak reduction is limit by systems that are actually operating on peak.
- What is the optimum user control/interface. There is evidence that traditional thermostat interfaces are not the best. There needs to be some fairly transparent and intuitive use interface that allows interactions with the other functions (current and planned) increasing present in modern thermostats.
- How should the DR signal interact with other load changing systems/appliances. For example shutting off ventilation systems and then operating the ventilation system at a higher flow rate off peak to compensate.
- Social equity. Is it easier for some people to respond than others?
- Should the critical peak be non-overrideable - how much occupant dissatisfaction result. In a non-mandatory program this is more important - but even in a mandatory program users will find ways to bypass controls that irritate them sufficiently.
- Should DR thermostats prevent setbacks earlier in the day before peak to avoid pulldown issues contributing to more peak operation. However, this makes the impact of DR harder to interpret. If homes start out cooler this leads to less air conditioning on peak - which we want - but will reduce the impact of DR.
- To what extent are Californian’s already manually doing DR.
- How will time of use rates or critical peak pricing influence thermostat settings and operation requirements? e.g., if an increase in TOU or a CPP signal could be sent to a thermostat it could change setpoints in a similar way to that proposed for DR.