# THERMOSTAT STRATEGIES FOR DISCRETIONARY HEATING AND COOLING OF DWELLINGS IN TEMPERATE CLIMATES

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ABSTRACT

This paper examines the simulation of heating and cooling events in dwellings for mild temperate climates. In this situation the initiation of events is usually at the discretion of the dwelling occupant.

The paper discusses aspects of dwelling heating and cooling behaviour derived from recent research on thermal sensation and preferences. Several different control strategies derived from this research data are introduced and their appropriateness considered.

Using the thermal evaluation program *EnCom2* the effects of adopting different simulation control strategies are examined.

The conclusion suggests that current simulation control strategies are inadequate to deal with real occupant behaviour and that research is necessary to provide models which can ensure suitable design advice.

## INTRODUCTION

*"To anyone infected with the idea that the human mind is unlimited in its capacity to answer questions about natural and human affairs, a tour of 20th century science must be quite a depressing experience. Many of the deepest and most well-chronicled results have been statements about what cannot be done and what cannot be known." (Casti, 1997)*

Building thermal performance simulation software developers generally assume the output of their program approximates reality and treat the results as such. However where the simulation involves the interaction of a physical building/plant model and a human action model "real" results can never be known. The implications for design advice under this condition of uncertainty must be appreciated.

Most thermal computer simulation techniques have heating and cooling control strategies which in essence assume the event initiation is under some form of mechanical (or electronic) control. A usual underlying assumption is that the building occupants will on the whole wish to provide "thermal comfort" conditions. Previous authors (Kempton et al, 1992; Lutzenhiser, 1992) have highlighted the confounding and variable manner of occupant use of air-conditioning appliances. Assumptions about thermostat settings and control strategies are however critical in determining realistic energy consumption figures upon which to base building design decisions. The problem comes into sharp focus in temperate climates where the balance between summer and winter energy consumption is a crucial factor and usually determines the nature of design advice.

In these relatively mild climates heating and cooling events in dwellings (that is, turning on and off appliances) are usually at the discretion of the occupants as opposed to being subject to automatic control. Once an appliance is turned on its operation may or may not be under the control of a thermostat, or the thermostat may be operated by the occupant as Lutzenhiser (1992) suggests by considering it to be a valve capable of continuous adjustment. The information concerning this aspect of thermal computer simulation is far from adequate because little comprehensive work has been done on determining thermostat or thermostat-like settings applicable in practice (as opposed to studies on thermal comfort) nor is there adequate data on what happens once heating or cooling has commenced.

This paper examines this issue using data derived from recent Australian studies. Analysis of the data highlights the difference between using aggregated results as opposed to strategies based on individual household behaviour.

## REAL OCCUPANT BEHAVIOUR

The complicated nature of the simulation problem is illustrated when we observe four key facts of occupant behaviour.

First, the reaction of people to a sense of being cold or hot is not necessarily to operate a heater or cooler, nor is such a reaction generally the sole response. Adjusting clothing, altering activity levels etc. are also common responses. The variety of reactions can be seen from the results of a questionnaire administered in Adelaide and Sydney as part of a project (the NEEHA project) to compare the performance of samples of energy-efficient and "standard" dwellings (Ballinger et al, 1991). A summary of the answers to a multiple response question(s) "*What is your response to cold/hot conditions?*" are shown in Tables 1 & 2. Although the most usual response to cold conditions is seen as "use heater" other responses can also be seen as important. The most usual response to hot conditions is not "use cooler" but rather "provide ventilation".

A second complication can be seen in another set of results derived from the NEEHA project. Neither the desirability nor the necessity of providing thermal comfort under all situations and at all times can be assumed. Williamson et al. (1989) had earlier raised the possibility that,

*"thermal neutrality cannot be assumed to be a goal in all built environments. And, even where it is found to be a relevant goal, it cannot be assumed that the costs of providing thermal neutrality will be considered justified by the occupants and/or by those who pay the building's construction and running costs. Further, it cannot be assumed that the non-monetary costs of providing thermal neutrality will be considered justified: plant noise, perceived health risks, and loss of close relationship with outdoors are examples of possible non-monetary costs which may be associated with the provision of thermal neutrality by air-conditioning plant".*

The results of the NEEHA project confirmed this suspicion. Combining the data for all locations and seasons studied during the Project, Table 3 shows the cross-tabulation to the question on the *Environment Response Logger*[1] panel *"How do you feel?"* and *"How would you like to feel?"*. The response to the former question is referred to as the VOTE and the latter as HOW.

This cross-tabulation shows that people do not always equate not wanting to feel any different ("no different") with "neither cool nor warm." Taking both samples together a significant number of people (23.8%) voted either "slightly cool" or "slightly warm", and even "warm" and "cool", together with a corresponding "no different" indicating their preference was not thermal neutrality. Anecdotal evidence gained during the project interviews with householders suggested that one explanation is that when people are operating heating or cooling appliances they wish to "feel" the effect. The assumption inherent in most heating/cooling control strategies that the desired state is one of thermal neutrality or comfort is at variance with this behaviour.

Thirdly many heating and cooling events are initiated and ended for other than strictly thermal reasons. Reasons for heating and cooling discovered during interviews with occupants include, *"I often put the heater on to dry the clothes*", *"We put the heater on when we come home", "I usually turn the heater on when I get up in the morning", "We turn the cooler on just before visitors are expected to arrive", "The kids turn on the air-conditioner when they come home from school"*. Analysis of interview results indicate that at least 25% of heating and cooling events fall into the non-thermal category.

Finally aspects such as cost, contextual factors, for example, plant noise, external temperature and social custom appear also to influence heating and cooling behaviour patterns. One occupant in a recent study discovered that the use of a reverse-cycle air-conditioner cost only about half as much per hour as she believed. Asked what, if any, effect this had upon her use of the appliance, she replied *"Well, I use it about twice as much now!"*.

Any simulation of thermal behaviour, including estimates of energy consumption, must attempt to take these "real" actions into account if the design information derived from the simulations is to be useable for comparing design options eg. more or less equator facing glass.

## THERMAL COMFORT BACKGROUND

Most heating and cooling event control strategies in thermal simulation remain tied to the notion that thermal comfort is the desired internal condition. A brief background to thermal comfort issues as they relate to control strategies is presented below.

Most of the research in the field of thermal comfort may be classified into two broad groups, according to the range of factors studied and the methodology adopted. First *laboratory based* (or climate chamber) methods tend to emphasise the effect of the physical environment on human thermal comfort, to the exclusion of other factors such as habit or cultural background. The effective temperature scale *ET* (Houghton & Yagloglou, 1923), the rational effective temperature scale *ET** (Gagge et al., 1971) together with *TSENS* and *DISC* (Gagge et al., 1986) are indices of thermal comfort which are outcomes of laboratory investigations. The ASHRAE *Comfort Zone(s)* (ASHRAE, 1992) owes its origin to this body of work. Probably the best known and most

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[1] The *Environment Response Logger* is an electronic instrument designed to record subjective thermal sensation responses and objective measures of indoor climate conditions. The householders entered information in five categories, thermal sensation, thermal preference, clothing, activity and perceived air movement. A 1-7 thermal sensation scale and a 1-3 preference scale are used on the *Loggers*. When respondents completed a "vote" the device recorded the prevailing dry bulb temperature and relative humidity and in addition the date and time.

widely accepted comprehensive thermal comfort index is Predicted Mean Vote (PMV) developed by Fanger (1972). For a given set of environmental variables the mean vote of a population expressed on a 7-point thermal sensation scale may be calculated, compatible with their metabolic rate and clothing levels. The international standard ISO 7730 *Moderate Thermal Environments - Determination of the PMV and PPD indices and the specification of the conditions for thermal comfort* (ISO-International Organisation for Standardisation, 1984) is based upon this relationship and is predicated on the belief that thermal comfort is a universal phenomenon unrelated to the context

The major criticism of models for predicting thermal comfort which are based solely on laboratory investigations is that field surveys have shown consistently that people adapt to their surroundings and accept conditions that would appear to lie outside the established comfort range(s). Researchers undertaking *field studies* assert the importance of environmental factors and claim that in practice, people are comfortable in a wide range of environments as they respond to the complex situations encountered in their daily life. This does not mean that given the opportunity, they would not "vote" for a comfort temperature in accordance to that predicted by the models - only that in complex real-life situations, behaviour patterns are modified so that comfort may be maintained at temperatures close to those to which people are actually exposed.

The work of Humphreys in 1975 drew attention to this issue when he presented an analyses of 36 field surveys, totalling over 200,000 observations, conducted by other researchers into the question of human thermal comfort (Humphreys, 1975). He found a very strong relationship between the neutral temperature[2] indicated by respondents in free-running buildings and the mean temperature to which they were exposed. The work of Auliciems in Australia (Auliciems, 1983) confirmed this type of relationship.

Later Humphreys (1978) showed that, for free-running buildings, the neutral or comfort temperature is related to the mean monthly external temperature by the expression ($R^2$=0.95),

$$T_n = 0.53\, T_m + 11.9 \quad \text{......... Eq. 1}$$

where $T_n$ is the neutral temperature in deg C,

$T_m$ is the mean outdoor temperature defined as *($T_{ave\ max} + T_{ave\ min}$)/2.*

[2] Neutral temperature is that temperature at which 50% of a sample population will indicate on a 7-point thermal sensation scale as in the range 1-4 and 50% in the range 4--7. It is usually considered synonymous with comfort temperature.

In the same study Humphreys found a similar but weaker relationship ($R^2$=0.52) for climate controlled buildings and this he suggested was best described as an exponential equation,

$$T_n = 23.9 + 0.295(T_m - 22)\, e^{-\left(\frac{T_m - 22}{24\times\sqrt{2}}\right)^2} \quad ..$$

Eq. 2

The equations 1 and 2 are plotted in Figure 1.

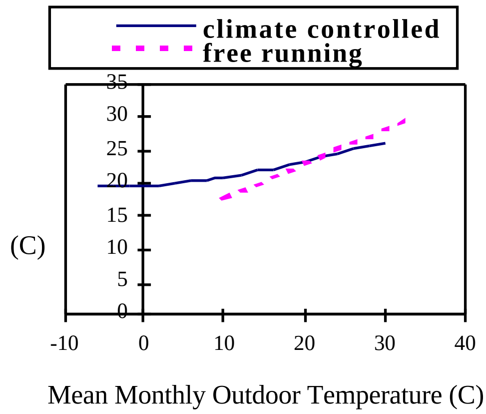


**Figure 1: Comfort Temperatures**

***Source: Derived from Humphreys, 1978***

The implication suggested from this data is that, in warm to hot climates ($T_m$>23°C), people in free-running or naturally ventilated buildings are prepared to accept a higher neutral temperature compared with people in air-conditioned buildings. In cold climates the opposite is true. Dwellings in mild temperate climates with intermittent heating and cooling can be considered as essentially free-running.

Auliciems (1983) using Australian field studies in combination with selected Humphreys data derived several modified equations which are based on combined data from free-running and climate-controlled buildings. He suggested a relationship between the mean external temperature and the neutral temperature as shown in Equation 3.

$$T_n = 0.31\, T_m + 17.6 \quad \text{............ Eq. 3}$$

In a similar analysis of the NEEHA project data which essentially involved free-running buildings Riordan (1992) found a good correlation between the neutral temperature and the mean external temperature ($R^2$=0.89) as shown in Eq. 4.

$$T_n = 0.537\, T_m + 11.0 \quad \text{............ Eq. 4}$$

These results add to a body of evidence which suggests that the predictions of thermal comfort based on theoretical heat-exchange models derived from laboratory experiments show significant discrepancies compared to the findings from field studies, putting in doubt estimates of thermal acceptability based on such models. The main contention put forward by a number of researchers [3] is that the models do not adequately account for various contextual factors, in particular the apparent changes in preferred environmental conditions as a function of the varying external conditions.

## ADAPTIVE MODELS

Contemporary thermal comfort studies attempt to address the contextual nature of the thermal environment requirements. Humphreys (1995) suggested the development of an adaptive model which would include factors to modify an accepted thermal comfort index to account for contextual aspects.

Williamson et al. (1995) have shown that an adaptive design assessment index may be developed and that estimates of the actual mean vote (AMV) found in field studies may be found from the estimated PMV with good accuracy. As shown in Figure 2 analysis of field study comfort data shows that a strong relationship ($R^2$=0.87) can be derived relating PMV-AMV to the mean external temperature. The data are derived from comfort surveys in Australia (Ballinger et al, 1991; Williamson, Coldicutt, & Penny, 1989, 1991) with additional limited data from Papua-New Guinea (Ballantyne et al, 1979), the UK (Oseland, 1994), Uganda (Olweny, 1996) and Pakistan (Nicol et al, 1994).

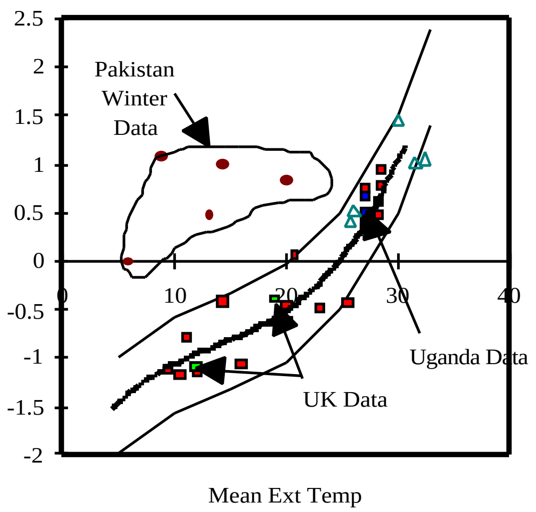


**Figure 2: Adaptive PMV Model**

The relationship between the PMV-AMV and the mean external temperature is shown in Eq. 5.

$$PMV - AMV = 000027\,T_m^3 - 001126\,T_m^2 + 020275\,T_m - 2.25$$

.......... Eq. 5

[3] For detailed discussion see Humphreys, 1994)

Figure 2 also shows a ±0.5 [PMV-AMV] error band indicating that most of the data falls within these limits. An interesting departure from the general trend is data collected in Pakistan during winter by Nicol et al. (1994). This data highlights the need to consider the contextual factors (in this case possibly cultural factors) when suggesting appropriate thermal comfort levels.

## HEATING/COOLING CONTROL STRATEGIES

In the absence of more complete data, control strategies for heating and cooling events based on thermal comfort theory can be envisaged to control thermal performance computer simulation. A number of possible models are described below and these are evaluated for their effectiveness and usefulness.

### On-off strategy

The simplest control strategy is a simple on-off mechanism where temperatures below a certain set-point will initiate a heating event and temperatures above a given temperature will initiate a cooling event. The set-point temperatures used in a simulation may be, for example, the upper and lower comfort zone conditions specified in standards such as ASHRAE 55-92 or a suitable climate modified neutral temperature as expressed in Equations 1,2,3 & 4 above.

### Thermostat-like climate modified strategy

A thermostat-like climate modified strategy may be proposed where the upper and lower bound limits are defined in relation to perceived comfort conditions. In practice this means a thermostatic type model were the upper and lower band set-points are automatically adjusted each month in accordance with the observed relationship between neutral temperature and the mean external temperature.

For example, by examining NEEHA Project data using a Probit regression technique as described by Ballantyne et al. (1977) and binning data by location and season, Riordan (1992) found that the 50th percentile thermal sensation vote transition temperatures[4] “Neutral/Slightly Warm” and “Slightly Cool/Neutral” (see Figure 3) are related to the mean external temperature for the variety of climates and seasons studied. These results may be used to infer a thermostat-like setting at which people will initiate a cooling or heating event. From the predicted percentage dissatisfied (PPD) distribution shown in ISO 7730 (p3, Table1) we can derive that a shift of approximately ±0.5 of a vote interval from a neutral

[4] The 50th percentile thermal sensation vote transition temperatures correspond to the temperatures when 50% of people will have changed their vote from neutral to slightly warm or neutral to slightly cool.

condition will result in an approximate 10% increase in occupant dissatisfaction. Adopting this value as a design criterion, an internal temperature mid-way between the neutral temperature and the 50th percential "Neutral/Slightly Warm" could be regarded as a mean *cooling commencement* temperature. By the same logic, the mid-point between the neutral temperature and the 50th percentile "Slightly Cool/Neutral" temperature, could be regarded as a mean *heating commencement* temperature.

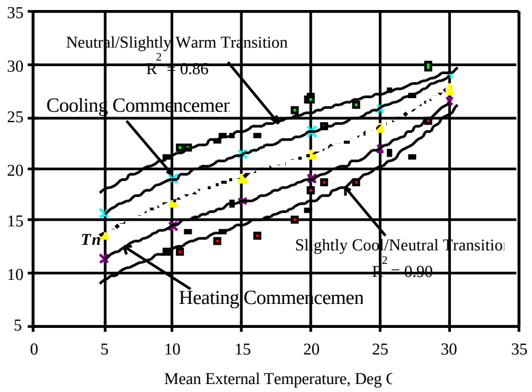


**Figure 3: Thermostat-like Model**

Although heating/cooling commencement temperatures are shown in Figure 3 as cubic relationships, with sufficient accuracy, these may be represented by linear equations with the *cooling commencement* line as,

$$T_{ci} = 0.50\ T_m + 13.6 \quad \text{............} \qquad \text{Eq. 6}$$

and the *heating commencement* line as,

$$T_{hi} = 0.57\ T_m + 8.5 \quad \text{.............} \qquad \text{Eq. 7}$$

A thermostat/behavioural model can be proposed as a logical expression,

if( $T_i > T_{ci}$ then cooling and $T_i = T_n$ )

else

if( $T_i < T_{hi}$ then heating and $T_i = T_n$ )

A limitation to this notions is however clear from the results in the thermal sensation and preference cross tabulations presented in, Table 3, because people indicate that they sometimes wanted to be other than "neutral". A further limitation, of course, is that we do not know from any of this data what will happen after heating or cooling have commenced.

Preliminary data from a current project (the Mary Street project) further highlights the limitation and unsatisfactory nature of this and the on-off approach. Figure 4 shows initial and final temperatures for heating events where occupants appeared to be present (indicated by a change in electrical load or hot water consumption) for at least the previous one hour, for households with reverse-cycle air-conditioning units.

Comparing Equations 4 & 6 (both shown superimposed on Figure 4) with the actual heating actions indicates behaviour far more complex than can be explained by an assumption that the thermal comfort or thermal neutrality is the main goal. Compared with the neutral temperature a significant degree of over-heating can be seen. A similar complex behaviour related to cooling events can be seen in Figure 5. where significant degree of "over-cooling" compared with comfort conditions is apparent. A further confounding factor, not shown in these figures, is that different behaviours are observed with resistive fan heaters and RC heating appliances.

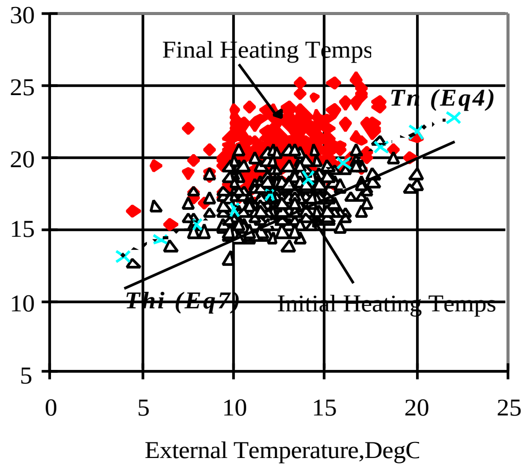


**Figure 4: Living Room Heating Events**

*Note: Heating events lasting at least 1 hour, with occupancy for at least one hour before initiation*

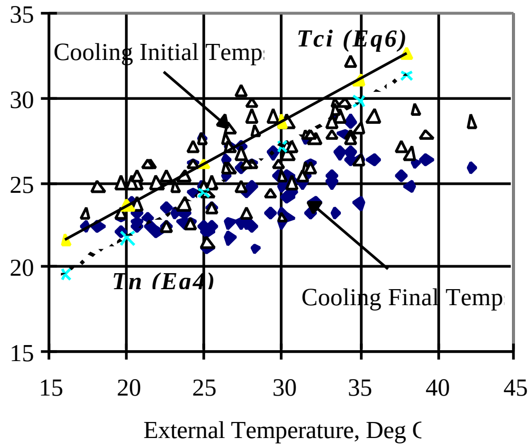


**Figure 5: Living Room Cooling Events**

*Note: Cooling events lasting at least 1 hour, with occupancy for at least one hour before initiation*

## Comfort Control Strategy

Several authors have discussed the advantages of using the PMV notion to control air-conditioning systems to achieve specified comfort levels (see for example, Lam, 1995; Thellier et al, 1991). A strategy involving PMV (or more properly, AMV as described above) may be employed to anticipate occupant behaviour for discretionary heating and cooling. The flow chart Figure 6 proposes that, in line with aspects of real behaviour, it is possible to simulate a heating/cooling strategy in which clothing levels are altered as an initial step to achieve comfort and then, if discomfort still exists as indicated by an estimated PMV (or AMV) value ±0.5 from comfort, then heating or cooling will be commenced by the occupant.

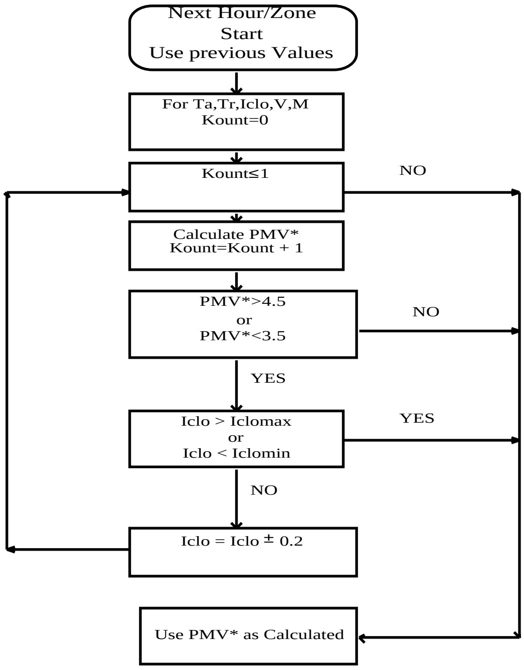


**Figure 5: PMV Comfort Control Strategy**

## SIMULATION OUTCOMES

The influence of these strategies on heating and cooling loads (and energy consumption) was examined using the computer program *EnCom2*. The results given in Table 4 clearly show that different control strategies give different balances between heating and cooling loads. Depending on the control strategy employed different design solutions could be judged the most appropriate.

## CONCLUSION

Building thermal performance simulation developers and users should be aware that assumptions on occupant heating and cooling behaviour built into most software packages are crucial in determining the building design advice which may flow from simulation results.

The conclusions suggested in this paper are that,

1. when heating and/or cooling events are at the discretion of dwelling occupants “real” heating and cooling behaviour cannot be predicted with any degree of confidence by an application of thermal comfort theory, and
2. if thermal comfort theory is applied in a control strategy as a rough predictor, the outcomes are sensitive to the nature of the chosen strategy.

The implications are clear. Further work is needed to determine suitable occupant behaviour models for simulation and to understand the effect that different models may have on the nature of design advice.

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**Table 1: Response to Cold Weather- Sydney & Adelaide**

| Most Frequent Responses | Sydney | Adelaide |
|---|---|---|
| | % of Cases | % of Cases |
| Use heaters | 120.1 | 169.2 |
| Wear warmer clothing | 74.3 | 64.1 |
| Close drapes/blinds at night | 65.7 | 59.0 |
| Allow direct sun in | 60.0 | 25.6 |
| Close inter-zone doors/selectively heat areas | 51.5 | 35.9 |
| Close windows/doors | 45.7 | 30.8 |
| Move to another room | 34.3 | 23.1 |
| Use electric blanket/heated waterbed | 25.7 | 28.2 |
| *All other responses* | 85.6 | 100.0 |

*Note: Multi-response question "What is your response to cold weather conditions?" Respondents may give more than one answer.*

**Table 2: Response to Hot Weather- Sydney & Adelaide**

| Most Frequent Responses | Sydney | Adelaide |
|---|---|---|
| | % of Cases | % of Cases |
| Provide ventilation | 68.6 | 76.9 |
| Close drapes and blinds during day | 65.7 | 66.7 |
| Wear less clothing | 91.4 | 64.1 |
| Close windows/doors to exclude heat | 74.3 | 61.5 |
| Use fans/cooling | 57.1 | 43.6 |
| Swimming / use sprinkler / beach | 45.7 | 35.9 |
| Move to another room | 28.6 | 33.3 |
| Decrease activity | 42.9 | 20.5 |
| Go outside to a shaded area | 22.9 | 17.9 |
| *All other responses* | 271.4 | 225.8 |

*Note: Multi-response question "What is your response to hot weather conditions?" Respondents may give more than one answer.*

**Table 3: Cross-tabulation of Vote vs How (% of total votes)**

| Standard houses | | | | | Energy Efficient houses | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | ***HOW*** | | | | | ***HOW*** | | | |
| ***VOTE*** | 1 | 2 | 3 | TOTAL | ***VOTE*** | 1 | 2 | 3 | TOTAL |
| 1 | 0.1 | 0.0 | 1.0 | **1.0** | 1 | 0.0 | 0.0 | 0.4 | **0.4** |
| 2 | 0.0 | 0.3 | 3.1 | **3.4** | 2 | 0.1 | 0.5 | 2.0 | **2.6** |
| 3 | 0.2 | 5.7 | 13.3 | **19.2** | 3 | 0.3 | 6.1 | 8.5 | **15.0** |
| 4 | 0.6 | 49.3 | 1.5 | **51.4** | 4 | 0.5 | 53.1 | 1.8 | **55.4** |
| 5 | 5.3 | 10.8 | 0.9 | **16.9** | 5 | 3.6 | 12.7 | 0.5 | **16.8** |
| 6 | 2.6 | 4.1 | 0.1 | **6.9** | 6 | 1.9 | 7.0 | 0.1 | **9.0** |
| 7 | 0.8 | 0.3 | 0.1 | **1.2** | 7 | 0.5 | 0.1 | 0.1 | **0.6** |
| **TOTAL** | 9.6 | 70.5 | 19.9 | 100.0 | **TOTAL** | 6.8 | 79.6 | 13.5 | 100.0 |

NOTE: VOTE: 1-cold, 2-cool, 3-sl.cool, 4-neither cool or warm, 5-sl.warm, 6-warm, 7-hot
HOW: 1-cooler, 2-no different, 3-warmer

**Table 4: Heating & Cooling Loads for Different Control Strategies**

| Strategy | Annual Heating Load(GJ) | Annual Cooling Load (GJ) | Ratio Heating/Cooling |
|---|---|---|---|
| **On-Off** | | | |
| ASHRAE 52-1992 | 18.4 | 1.9 | 9.68 |
| Equation 4 | 8.4 | 7.2 | 1.16 |
| **Thermostat-like** | | | |
| Equations 6(cool) & 7(heat) | 6.3 | 7.2 | 0.87 |
| **Comfort Controller** | | | |
| PMV | 9.0 | 3.5 | 2.57 |
| AMV | 7.5 | 3.7 | 2.02 |