Climate, Comfort, & Natural Ventilation: A new adaptive comfort standard for ASHRAE Standard 55

G. S. Brager[*] R. de Dear[†]

[*]Center for Environmental Design Research, University of California, Berkeley
[†]Division of Environmental and Life Sciences, Macquarie University

Climate, Comfort & Natural Ventilation:
A new adaptive comfort standard for ASHRAE Standard 55

Gail S. Brager[1] and Richard de Dear[2]

[1] Center for Environmental Design Research, University of California, Berkeley, CA 94720-1839 USA
Ph: 510-642-1696, Fax: 510-642-5571, E-mail: gbrager@socrates.berkeley.edu

[2] Division of Environmental and Life Sciences, Macquarie University, Sydney NSW 2109 Australia

ABSTRACT

Recently proposed revisions to ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy*, include a new adaptive comfort standard (ACS) that allows warmer indoor temperatures for naturally ventilated buildings during summer. The ACS is based on the analysis of 21,000 sets of raw data compiled from field studies in 160 buildings, both air-conditioned and naturally ventilated, located on four continents in varied climatic zones. This paper summarizes this earlier research, presents some of its findings for naturally ventilated buildings, and discusses the process of getting the ACS incorporated into Std. 55. We suggest ways the ACS could be used for the design, operation, or evaluation of buildings, and for research applications. We also use GIS mapping technology to examine the energy-savings potential of the ACS on a regional scale. Finally, we discuss related new directions for researchers and practitioners involved in the design of buildings and their environmental control systems.

Conference Subject: Adaptive Comfort Theory

Keywords:
thermal comfort, adaptation, field studies, natural ventilation, energy conservation

Introduction

The purpose of ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy, is "to specify the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a space" (ASHRAE 1992). While "acceptability" is never precisely defined by the standard, it is commonly accepted within the thermal comfort research community that "acceptable" is synonymous with "satisfaction", and that "satisfaction" is indirectly associated with thermal sensations of "slightly warm", "neutral", and "slightly cool", and that "thermal sensation" is the question most commonly asked in both laboratory and field studies of thermal comfort.

What, then, influences people's thermal sensations? ASHRAE Standard 55 is currently based on the heat balance model of the human body, which predicts that thermal sensation is exclusively influenced by environmental factors (temperature, thermal radiation, humidity and air speed), and personal factors (activity and clothing). An alternative (and, we believe, complementary) theory of thermal perception is the adaptive model, which states that factors beyond fundamental physics and physiology play an important role in impacting people's expectations and thermal preferences. Thermal sensations, satisfaction, and acceptability are all influenced by the match between one's expectations about the indoor climate in a particular context, and what actually exists. While the heat balance model is able to account for some degrees of behavioral adaptation (such as changing one's clothing or adjusting local air velocity), it is not able to account for the psychological dimension of adaptation, which may be particularly important in contexts where people's interactions with the environment (i.e., personal thermal control), or diverse thermal experiences, may alter their expectations, and thus their thermal sensation and satisfaction. One context where these factors play a particularly important role is naturally ventilated buildings

Happily, we're seeing an increasing number of architects and engineers paying attention to the cry of occupants for operable windows in non-residential buildings. Unfortunately, they are often limited in their flexibility to pursue such options because of the relatively narrow range of interior thermal environments allowed by ASHRAE Standard 55, and assumed to be universally applicable across all building types, climates, and populations. Although it was never intended for ASHRAE Standard 55 to *require* air-conditioning for buildings, practically it is very difficult to meet the standard's narrow definition of thermal comfort without such mechanical assistance, even in relatively mild climatic zones. And the energy costs of providing this constant supply of uniformly conditioned air are significant, as are the well-known environmental consequences associated with this vast energy consumption.

How can thermal comfort standards play a role in facilitating the appropriate use of energy-efficient, climate-responsive building design strategies? The first step is to recognize that comfort depends on context. People living year-round in air-conditioned spaces are quite likely to develop high expectations for homogeneity and cool temperatures, and may become quite critical if thermal conditions deviate from the center of the comfort zone they have come to expect. In contrast, people who live or work in naturally ventilated buildings, where they are able to open windows, become used to experiencing inherently more variable indoor thermal conditions that reflect local patterns of daily and seasonal climate changes. Their thermal perceptions – both their preferences as well as their tolerances – are likely to extend over a wider range of temperatures than are currently reflected in the ASHRAE Std. 55 comfort zone.

To ASHRAE's credit they did recognize this, and funded research to quantify the difference between people's thermal responses in air-conditioned and naturally ventilated buildings. The outcome was a proposal for a new adaptive comfort standard to complement the traditional PMV-based comfort zone. This paper briefly describes and expands on the results of that project, *ASHRAE RP-884: Developing an Adaptive Model of Thermal Comfort and Preference*, and describes how the work is currently being incorporated into ASHRAE Std. 55, and how both practitioners and researchers might use the ACS. For greater detail about this project, previous papers describe the results of our literature search on thermal adaptation (Brager and de Dear, 1998), the specific procedures for developing the database (de Dear, 1998), and our analysis methods and findings (de Dear and Brager, 1998, Brager and de Dear, 2000).

Methods: Developing the ASHRAE RP-884 Database

In the mid-1980's, ASHRAE began funding a series of field studies of thermal comfort in office buildings in four different climate zones. They were specifically designed to follow a standardized protocol developed as part of the first in the series, ASHRAE RP-462 (Schiller et al, 1988). Since that time, numerous other thermal comfort researchers independently adopted the same procedures for collecting both physical and subjective data in their own field studies. In 1995, ASHRAE RP-884 began by collecting raw field data from projects around the world that had followed this standardized (or a similar) protocol, and/or where the data met strict requirements regarding measurement techniques used, type of data collected, and database structure. Standardized data processing techniques, such as methods for calculating clo and various comfort indices, were then applied consistently across the entire database (de Dear, 1998). This enabled RP-884 to assemble a vast, high-quality, internally consistent database of thermal comfort experiments. The RP-884 database contains approximately 22,000 sets of raw data from 160 different office buildings located on four continents, and covering a broad spectrum of climate zones. Locations include Bangkok, Indonesia, Singapore, Athens, Michigan, several locations each in California, England, and Wales, six cites across Australia, and five cities in Pakistan (see Figure 1). The data includes a full range of thermal questionnaire responses, clothing and metabolic estimates, concurrent indoor climate measurements, a variety of calculated thermal indices, and outdoor meteorological observations.

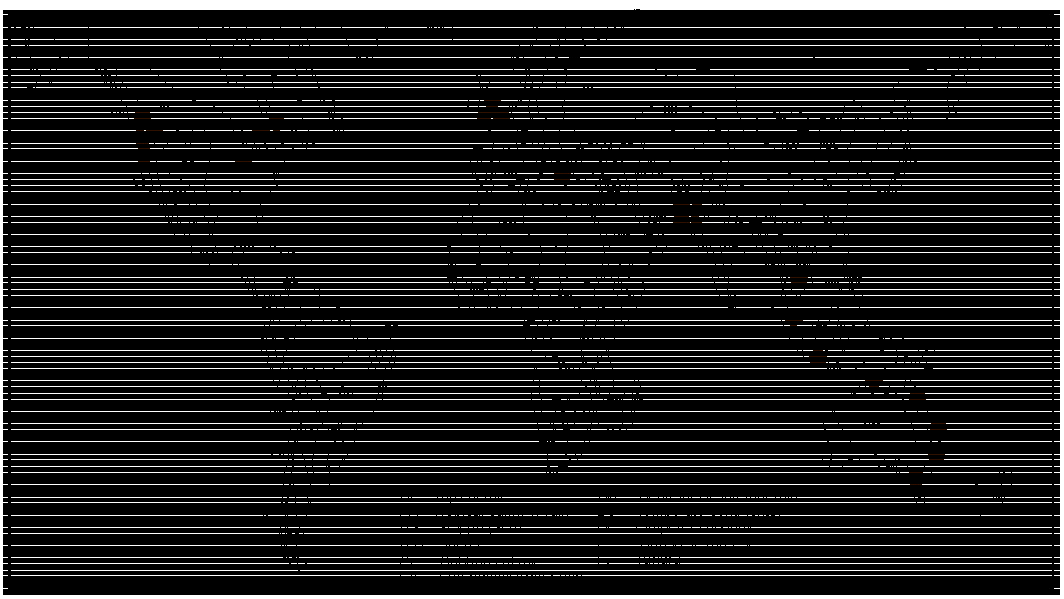

Figure 1: The geographic spread of building studies comprising the RP-884 thermal comfort database (adapted from Rudloff, 1981)

The buildings in the database were separated into those that had centrally-controlled heating, ventilating, and air-conditioning systems (HVAC), and naturally ventilated buildings (NV). Since the RP-884 database comprises existing field experiments, this classification came largely from the original field researchers' descriptions of these buildings and their environmental control systems. The primary distinction between the building types were that the NV buildings had no mechanical air-conditioning, and the natural ventilation occurred through operable windows that were directly controlled by the occupants. In contrast, occupants of the HVAC buildings had little or no control over their immediate thermal environment. Since most of the NV buildings were studied in the summer, in most cases the type of heating system was irrelevant. The few that were studied in winter may have had a heating system in operation, but it was of the type that permitted occupant control. Unfortunately, there were not enough hybrid ventilation (also called "mixed-mode") buildings in the RP-884 database to allow their separate analysis. All analysis was done separately for the HVAC and NV buildings, using each individual building as the initial unit of analysis, and then conducting a meta-analysis of the separate statistical calculations done within each building.

Results: Thermal Comfort in Naturally Ventilated Buildings

Figures 2a and 2b show some of the most compelling findings from our separate analysis of HVAC and NV buildings, shown in the left and right panels, respectively. (We believe that the clear differences in these patterns also vindicate our building classification scheme.) The graphs present a regression of indoor comfort temperature[1] for each building against mean effective temperature (ET*) as the outdoor temperature index. Regressions were based only on buildings that reached statistical significance ($p=0.05$) in the derivation of their own neutral or preferred temperature (as a result, 20 buildings in the RP-884 database had to be eliminated from this analysis because of small sample sizes or very homogeneous indoor climates). Each graph shows the regression based on both observed responses in the RP-884 database, and predictions using Fanger's PMV (1970). The original graphs presented in the RP-884 Final Report (de Dear et al., 1997) show the data points spread around the regression lines, but only the regression lines are shown here for simplicity.

Two strong patterns emerge from these graphs. First, the steeper gradient of observed responses (dotted line) in NV buildings (Fig. 2b) compared to HVAC buildings (Fig. 2a) suggests that occupants of HVAC buildings become more finely adapted to the narrow, constant conditions typically provided by mechanical conditioning, while occupants of NV buildings prefer a wider range of conditions that more closely reflect outdoor climate patterns.

Secondly, a comparison of the observed and predicted lines within each graph illustrates the role of adaptation in these two building types. In the HVAC buildings, PMV was remarkably successful at predicting comfort temperatures, demonstrating that behavioral adjustments of clothing and room air speeds (both of which are inputs to the PMV model) fully explained the relationship between indoor comfort temperature and outdoor climatic variation. In contrast, the difference between these two lines in the NV buildings shows that such behavioral adjustments accounted for only half of the climatic dependence of comfort temperatures. The rest must come from influences not accounted for by the PMV model, and our analysis suggests that psychological adaptation is the most likely explanation. In particular, we believe that indoor

[1] For this analysis, "preference" was considered as a more appropriate indicator of optimum thermal conditions than the traditional assumption of "neutral thermal sensation". In the HVAC buildings, preferred temperature was slightly warmer than neutral temperatures in cooler climates, and slightly cooler in warmer climates (by up to 1°C at either extreme end). There was no difference in the NV buildings. The indoor comfort temperature on the y-axis, therefore, includes a correction factor to modify calculations of neutral temperatures in HVAC buildings to more accurately reflect preference.

comfort temperatures in NV buildings are strongly influenced by shifting thermal expectations resulting from a combination of higher levels of perceived control, and a greater diversity of thermal experiences in the building.

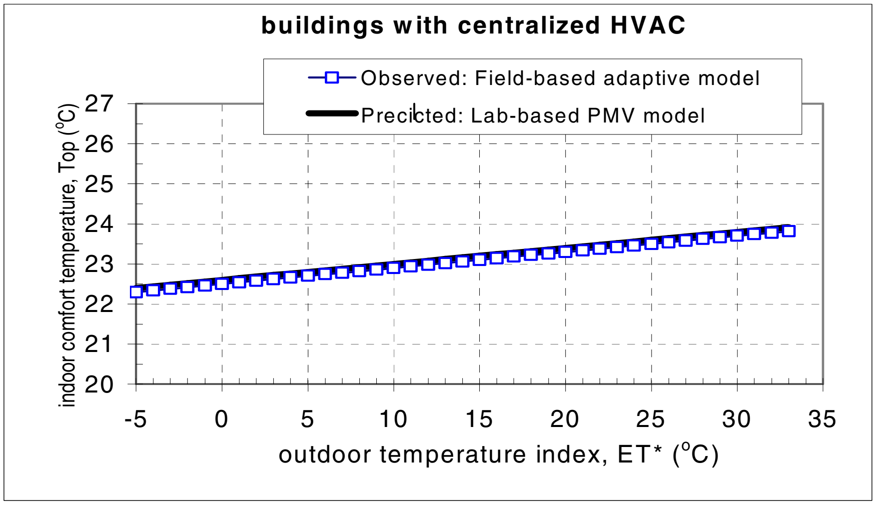

Figure 2a: Observed and predicted indoor comfort temperatures from RP-884 database, for HVAC buildings**.**

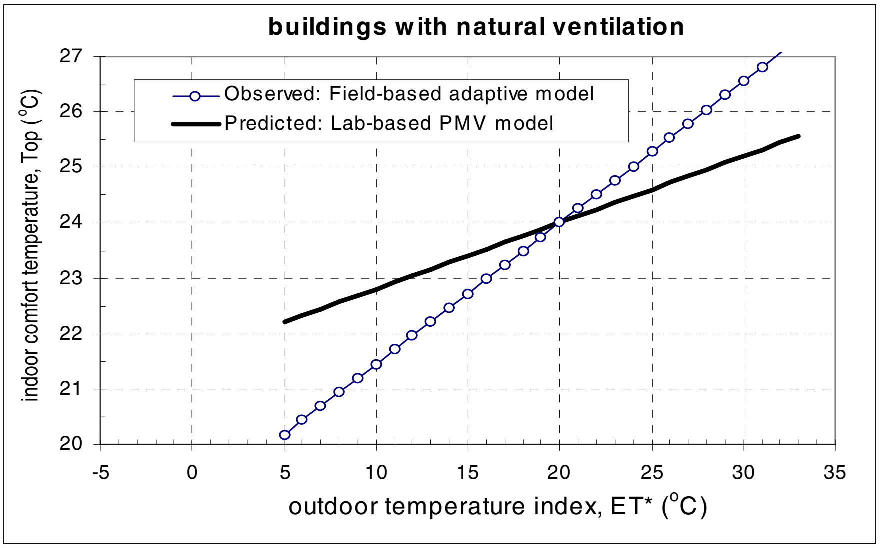

Figure 2b: Observed and predicted indoor comfort temperatures from RP-884 database, for naturally ventilated buildings

These findings led to a proposal for an adaptive comfort standard (ACS) that would serve as an alternative to the PMV-based method in ASHRAE Std. 55. The outdoor climatic environment for each building was characterized in terms of mean outdoor dry bulb temperature $T_{a,out}$, instead of ET*. Optimum comfort temperature, T_{comf}, was then similar to the regression shown in the right side of Figure 2, but re-calculated based on mean $T_{a,out}$:

$$T_{comf} = 0.31 \times T_{a,out} + 17.8 \quad \text{(deg C)} \qquad \text{(eqn. 1)}$$

The next step was to define a range of temperatures corresponding with 90% and 80% acceptability. Only a small subset of the studies in the RP-884 database had included direct assessments of thermal acceptability, and the analysis of these data was not statistically significant. We were, therefore, left with having to infer "acceptability" from the thermal sensation votes, and started with the widely used relationship between group mean thermal sensation vote and thermal dissatisfaction (i.e., the classic PMV-PPD curve). The PMV-PPD relationship indicates that a large group of subjects expressing mean thermal sensation vote of ± 0.5 (or ± 0.85) could expect to have 10% (or 20%) of its members voting outside the central three categories of the thermal sensation scale (assumed to represent dissatisfaction). Applying the ± 0.5 and ± 0.85 criteria to each building's regression model of thermal sensation as a function of indoor temperature produced a 90% and 80% acceptable comfort zone, respectively, for each building. Arithmetically averaging those comfort zone widths for all the NV buildings produced a mean comfort zone band of 5°C for 90% acceptability, and 7°C for 80% acceptability, both centered on the optimum comfort temperature shown in Eqn. 1. We then applied these mean values as constant temperature ranges around the empirically-derived optimum temperature in Eqn. 1. The resulting 90% and 80% acceptability limits are shown in Figure 3.

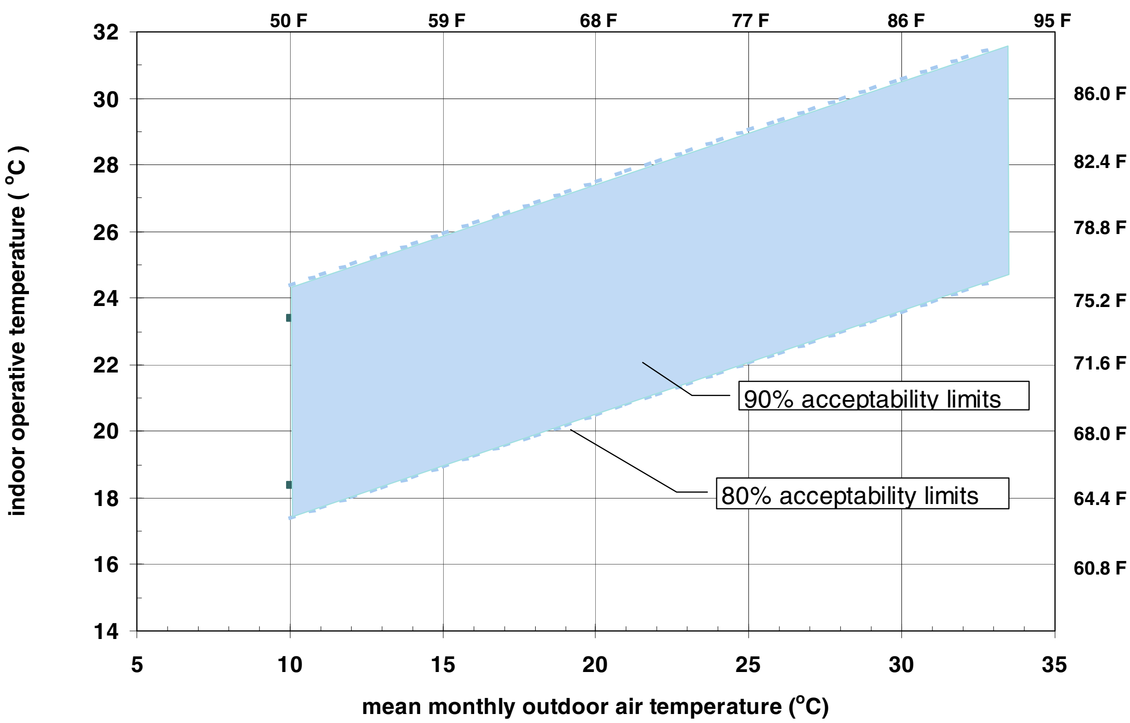

Figure 3: Proposed Adaptive Comfort Standard (ACS) for ASHRAE Std. 55, applicable for naturally ventilated buildings.

Note that Figure 3 is slightly different than the one originally produced by RP-884 (de Dear and Brager, 1998), and instead is the one that is being proposed for inclusion in ASHRAE Std 55. The decisions made to modify the original graph are described in more detail later in this paper. But before describing the process of getting Figure 3 incorporated into ASHRAE Std. 55, it may be useful to look in more detail at the NV buildings that were included in our analysis. Figures 4a and 4b show the operative temperatures and thermal sensations from each of the NV buildings in the RP-884 database[2], as a function of the mean outdoor air temperature that existed during a continuous part of the study that took place in a given month or season. For each line, the dot represents the mean of the measurements, and the lower and upper bands represent the 20th and 80th percentiles, respectively. Figure 4a also shows the 80% limits of the ACS model for reference. Note that most thermal sensation votes in the database were recorded as integer numbers, and so the percentile bars tend to fall on integer numbers as well. We chose to present the 20th and 80th percentiles because they would more accurately reveal any asymmetries around the mean, as compared to using the more traditional $\pm$ one standard deviation, which assumes a normal distribution.

A couple of clear patterns are seen in these graphs. First, below mean outdoor temperatures of 23°C, the NV buildings were primarily operating within the limits of the ACS, and mean thermal sensations were primarily within $\pm$ 0.5. This means that, despite relatively large climatic variations outside, interior conditions remained relatively stable and occupants were able to maintain neutral or close to neutral sensations. The few buildings that were operating above or below the ACS limits had corresponding thermal sensations that were, respectively, much warmer or cooler than neutral, as one might expect.

Above mean outdoor temperatures of 23°C, interior temperatures frequently rose above the ACS limits, with mean indoor operative temperatures clustered around 30°C (86°F), and simultaneous mean thermal sensations clustered around a mean vote of 1.0. So while the neutral temperatures for these buildings were calculated to be in the range of 26-27°C, the data suggests that these naturally conditioned buildings were not, in fact, able to maintain thermal comfort even as defined by the ACS model for many hours of the day. These buildings came from a range of climates and cultures, including various regions of Pakistan, Australia, Greece, Singapore, Indonesia, and Thailand. As a result, it's difficult to generalize about them or to cast them off as being representative of only a single region.

[2] Note that not all of the NV buildings in these figures were used in the development of the ACS shown in Figure 3, since some buildings were eliminated from the ACS analysis if their derived neutral or preferred temperatures did not reach statistical significance.

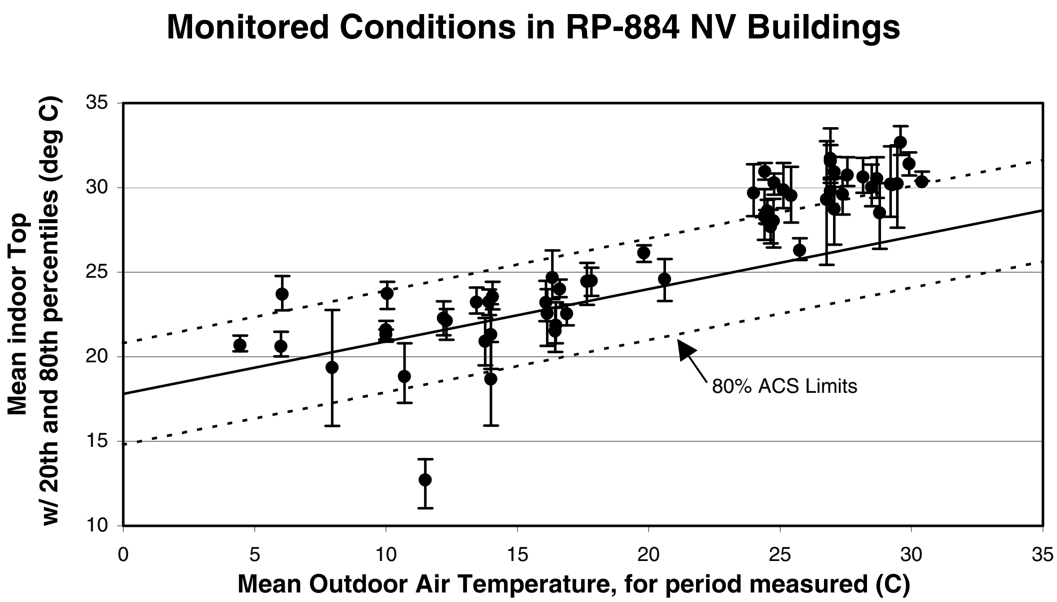

Figure 4a. Indoor operative temperatures in the naturally ventilated buildings of the RP-884 database.

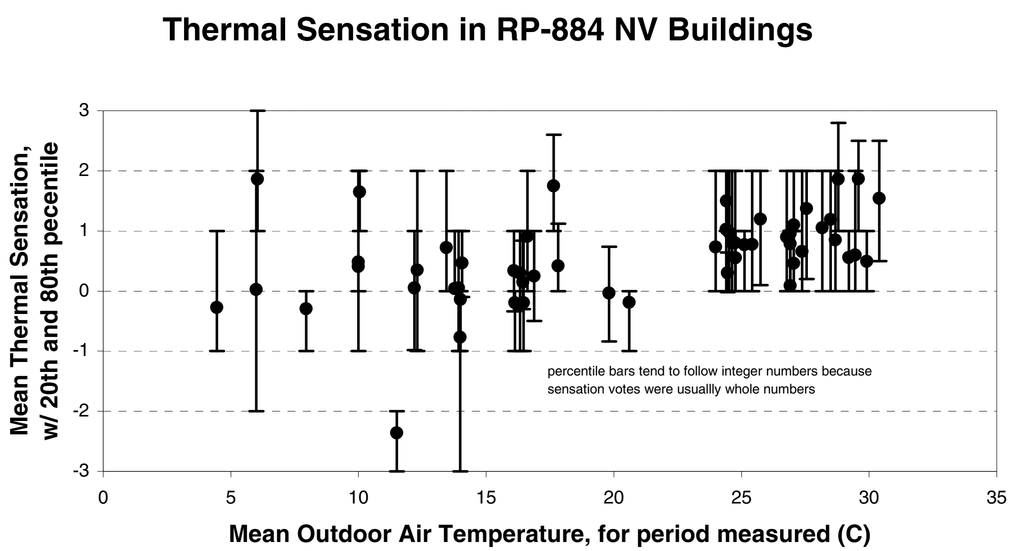

Figure 4b. Thermal sensations in the naturally ventilated buildings of the RP-884 database.

Creating an Adaptive Comfort Standard

Incorporating research into a thermal comfort standard is a very different process than conducting the research itself. While one expects researchers to conduct their work with rigor and impartiality, standards are produced through a process that inherently must balance scientific evidence with expert judgment, practical experience, simplifications, added assumptions, and compromises to compensate for the missing gaps in our knowledge. The ASHRAE Committee (SSPC 55) in charge of revising its thermal comfort standard is made up of members representing manufacturers, designers, building owners and users, researchers and educators. Because of the experience these members bring with them, they are expected to naturally have their own biases (and are required by ASHRAE regulations to declare them up front when they become members). These biases are clearly reflected in the committee's deliberations and are, in fact, a healthy and necessary part of the process (even during the times that deliberations may become quite heated because of the differences in opinion). But only by representing as many different stakeholders as possible on SSPC 55 can the revised standard have any real chance of adoption by the intended end-users. SSPC 55 minus this diversity of composition could be expected to develop a document of little more than academic interest.

In funding RP-884, it was always intended that this work would result in a proposal for what was then called a "variable temperature standard", to hopefully be incorporated into ASHRAE Std. 55. The findings of RP-884 were presented at the ASHRAE San Francisco meeting in January 1998 (de Dear and Brager, 1998), and in June 1998 SSPC 55 passed a motion to include (or at least consider) some type of an adaptive comfort standard in the next set of revisions to ASHRAE Std. 55. In the ensuing semi-annual meetings of SSPC, there were extensive discussions about the ACS. Many issues were raised, discussed at length, and eventually resolved through agreement, compromise, and capitulation. This section discusses some of those decisions. (For an overview of other changes being proposed for ASHRAE Std. 55, Bjarne (2000) describes the replacement of ET* with the PMV-based comfort zone, the introduction of different acceptability levels, changes in humidity limits, etc.).

The new ACS is presented in ASHRAE Std. 55 as "*Section 5.3. Optional method for determining acceptable thermal conditions in naturally conditioned spaces*". Note from the title that the traditional Std. 55 comfort zone is still universally applicable for all conditions, while the new ACS is offered as an <u>option</u> under certain limited conditions.

<u>Scope</u>. One of the biggest contested issues was the scope of applicability of Section 5.3, which right now is extremely limited (although that could, perhaps, still change depending on comments received during the public review stage). Currently, Section 5.3 can be used only for the following conditions:

- naturally conditioned spaces where the thermal conditions of the space are regulated primarily by the occupants through opening and closing of windows. It is specifically noted that the windows must be easy to access and operate.
- spaces can have a heating system, but the method doesn't apply when it is in operation.
- spaces cannot have a mechanical cooling system (e.g., refrigerated air-conditioning, radiant cooling, or desiccant cooling).
- spaces can have mechanical ventilation with unconditioned air, but opening and closing of windows must be the primary means of regulating thermal conditions.
- occupants of spaces must be engaged in near sedentary activity (1-1.3 met), and must be able to freely adapt their clothing to the indoor and/or outdoor thermal conditions.

Some people presented strong arguments that the ACS should be applicable to other situations where people have personal control, such as mixed-mode buildings or spaces (where both air-conditioning and operable windows are present), or task/ambient conditioning systems (TAC, where occupants have control over some aspect of local thermal conditions, and the ACS would be applied to the broader ambient conditions). The crux of these arguments was that the availability of personal control played a primary role in shifting people's thermal expectations, and so the ACS model is likely to be a more accurate representation of people's thermal responses in other realistic situations with personal control, compared to the laboratory studies. There is also evidence that people with TAC systems are comfortable over a much wider range of temperatures when they have control over those local conditions, and this pattern was very close to what was found in the naturally-ventilated buildings in the RP-884 database (Bauman et al., 1998). Other people argued that the ACS should be strictly limited to the same conditions under which the data was collected (i.e., the limitations summarized above). Some felt that this was placing a stricter standard of proof or interpretation for this field-based method, compared to the traditional laboratory-based comfort zone which is being universally applied to all conditions, even though it was developed under a comparatively smaller range of scenarios, and wasn't based on tests in any buildings at all. In the end, the more conservative positions prevailed, and the scope of Section 5.3 is limited to the conditions described above.

Characterization of outdoor climate. The original analysis of RP-884 expressed the ACS in terms of outdoor effective temperature (ET*). But it was agreed by everyone on SSPC 55 that ET* is primarily an index used by researchers, and that practitioners would be more likely to use the ACS if the meteorological input data was a more familiar and accessible index. The ACS was, therefore, reformulated in terms of mean monthly outdoor air temperature, defined simply as the arithmetic average of the mean daily minimum and mean daily maximum outdoor (dry bulb) temperatures for the month in question. This climate data is readily available and familiar to engineers.

Limits. The original analysis of RP-884 extended from a mean outdoor air temperature of 5-33°C. Several members of SSPC felt the lower end was too extreme (regardless of what the data actually showed), and there was some discussion as to whether the lower end of the graph should simply be arbitrarily truncated at a higher mean outdoor air temperature, or that it should be limited to non-heating conditions. In the end, both recommendations prevailed, and the ACS presented in Section 5.3 of Std. 55 ends at 10°C mean outdoor air temperature. It was also discussed whether the graph should end sharply at the end points, or whether the lines should extend horizontally when outdoor temperature extended beyond the 10-33°C. It was decided, appropriately, to limit the graph to the range of measured data, and specify that the allowable operative temperature limits may not be extrapolated to outdoor temperatures above or below the end points of the curve.

Range of acceptability. The original analysis of RP-884 first produced a regression line of optimum temperatures (derived from neutralities and temperature preferences) as a function of prevailing outdoor temperature. The 80% and 90% ranges were then determined as described in the previous section. SSPC 55 first decided that only a range, and not an optimum, should be presented as part of the ACS, and this was followed by debate about whether that range should be based on 80% or 90% acceptability limits. The discussion began by noting that the traditional comfort zone in ASHRAE Std. 55 was intended to represent 80% acceptability. Statistically, however, the limits are actually based on 10% dissatisfaction from general (whole body) sensations, represented by PMV=+0.5 and PPD=10%, plus an additional average 10% that may arise from local discomfort (note that PMV/PPD only accounts for whole body response derived from uniform laboratory conditions.) SSPC finally agreed that, as a field-based method, the 80% line of the ACS most accurately corresponded with 80% acceptability in the field, and was more consistent with the intent of the standard. Although no studies have been done to present undeniable evidence of this, it was agreed that the most appropriate interpretation was that people's responses in typical buildings in the field already integrate, or account for, the combination of whole body and local discomforts that they may be experiencing. Despite this agreement on the committee, it was still decided to present the graph with both the 80% and 90% lines. It is noted that the 80% is the most appropriate one to use for typical applications, but that the more narrow 90% acceptability limits may be used when a higher standard of thermal comfort is desired, of if there is reason to believe that high levels of local thermal discomfort may be a problem. We should also be reminded that the ACS is an optional standard – it provides recommendations, not code-enforceable requirements. People have the discretion to work within the limits allowed by the ACS, based on their own experiences, and the presumed expectations of the people who will be occupying their buildings

Using the Adaptive Comfort Standard

How might people actually use the ACS? Like any part of a thermal comfort standard, recommendations for acceptable indoor temperatures can be used during the design stage of a new building, or for the operation or evaluation of an existing building.

As a design standard (or, simply, a design tool) for naturally conditioned spaces, one might first use a building simulation tool to predict what indoor conditions might be achieved. The ACS could then be used to determine whether those thermal conditions are likely to be acceptable. If they are not acceptable, then design modifications might be made (i.e., to the thermal mass or fenestration), and the process repeated. If such changes prove to be ineffectual in subsequent simulations, a decision to air condition might then be appropriate.

If windows in a building were operated both manually and automatically, or if the ACS were eventually allowed to apply to mixed-mode buildings, perhaps it could also be used as an operating guideline. The interior temperatures might be allowed to float within the more energy-efficient acceptability limits of the ACS, and when the temperatures reached the maximum limits then the air-conditioning could be turned on in a limited way to ensure that temperatures stayed within the ACS limits (rather than switching to the narrow setpoints of a traditional, centrally-controlled air-conditioned building). The ACS could also be used in mixed -mode buildings to establish the interior design temperatures used for load calculations for sizing equipment. If the building was going to be operated within the wider limits of the ACS, this would allow the equipment to be downsized, resulting in potential cost-savings and space-savings as well.

If the ACS were allowed to apply to task/ambient conditioning systems, then the building's ambient environment could be allowed to float within the broader limits of the ACS, while the individual controls would allow occupants to control their local thermal conditions to achieve their preferred comfort levels.

The ACS could also be used to evaluate the predicted acceptability of existing thermal conditions in naturally conditioned spaces, in the same way that the PMV-based thermal comfort standard is used to evaluate the acceptability of thermal conditions in HVAC buildings. Some weighted time function could be devised to index the duration and intensity of temperature excursions outside the ACS zone and this might serve as a useful quality benchmarking tool for property managers.

In all these applications, one of the advantages of the ACS over the PMV-based model, for situations where it applies, is its simplicity. While one needs to estimate what mean clo and met levels might be before using the PMV model, the relationship between clothing and climate is already accounted for in the ACS.

The ACS is also intended for continued use as a research tool. The database is available on-line (http://atmos.es.mq.edu.au/~rdedear/ashrae_rp884_home.html), and it is our hope that other researchers will continue to use it to investigate new questions, or to validate new field data from buildings with operable windows, or perhaps with other forms of personal control.

Another potential application is the use of the ACS for regional climate analysis, as a way of investigating the feasibility of using natural ventilation, and the potential energy savings that might result. If a building's interior conditions were able to be maintained within the ACS limits entirely by natural means, then one could potentially save 100% of the cooling energy that would otherwise be used by an air-conditioner to maintain conditions within the more narrow ASHRAE Std. 55 comfort zone. If one were to apply the ACS to a mixed-mode building, however, the air-conditioner might be used in a limited way to keep the more extreme temperatures from rising past the acceptability limits of the ACS. In this case, the energy savings would be proportional to the difference between setpoints defined by the upper limit of the ACS, compared to typical setpoints used in an air-conditioned building.

Figure 5 presents an approach to this type of analysis, where we began with July climate data for the U.S., and then compared the upper 80% acceptability limit of the ACS to the upper limit of the ASHRAE Std. 55 comfort zone (based on 0.5 clo and 50% RH), which is 26°C. The map shows the regions of the country where the difference in comfort temperatures using these two methods ranges from 0-5 °C. Energy savings would be proportional to the difference in these setpoints. This is actually a conservative estimate, and savings are likely to be much higher than indicated since it is more common to operate buildings at the center of the ASRHAE Std. 55 comfort zone (approximately 23°C), rather than at the upper end of 26°C. It should be emphasized that is a preliminary application of applying GIS technology to thermal comfort analysis and is based on coarse data. However, the picture is still indicative of the large potential for saving energy by using natural ventilation instead of air-conditioning (assuming that people have direct control of the operable windows, and are also free to adapt their clothing). The map is also being shown as an example of combining thermal comfort prediction methods with GIS technology to expand our analysis to a regional scale.

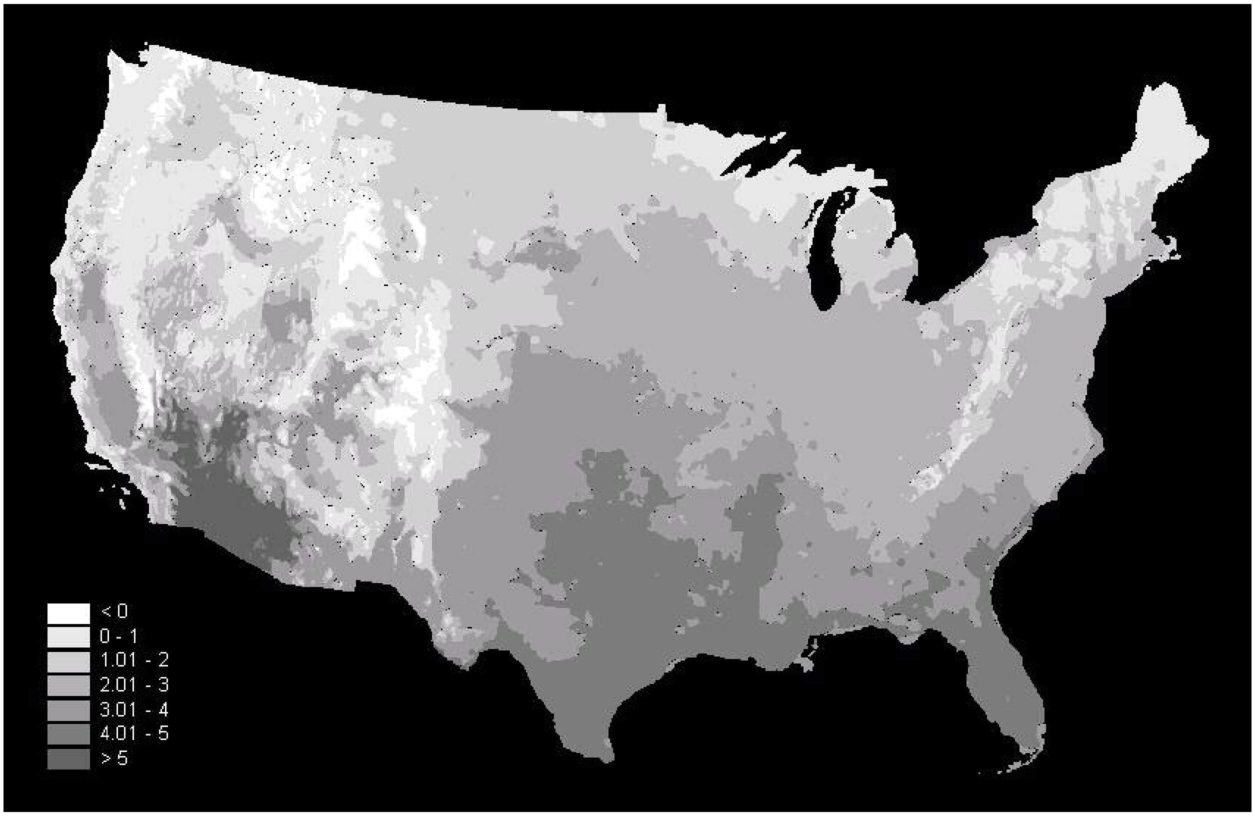

Figure 5. Comparison of recommended indoor comfort temperatures, upper limits of ACS vs. ASHRAE Std. 55. Darker areas indicate larger differences between setpoint temperatures, and therefore larger energy savings.

Moving into the 21st Century

Finally, we would like to address the primary objective of this conference – what new thermal comfort research is needed and how can it be incorporated into the development of new standards? The collective research that has formed the basis of the ACS has perhaps raised as many questions as it has answered, and we would like to highlight some key issues regarding the application of research and new standards towards improving the design and operation of buildings.

Satisfaction & Inter-individual differences. In developing the ACS, we applied the relationship between mean thermal sensation and % dissatisfied, as illustrated in the classic PPD vs. PMV curve. In doing so, we were adopting two broad assumptions that can continue to be investigated with further research. First is the traditionally used assumption that dissatisfaction is associated with votes of ± 2 and 3 on the 7-point ASHRAE thermal sensation scale (with 0 representing neutral). Is there a better way to assess dissatisfaction, or acceptability, than having to make this indirect association with thermal sensation votes? Unfortunately, direct assessments of acceptability often do not produce any statistically significant relationships with environmental measurements, and so the nature of such questions needs further study.

Perhaps even more important a research priority is the assumption that inter-individual differences are the same in both the laboratory and the field (this is at the heart of applying the lab-based PMV-PPD relationship to standards, that are then applied in the field). Is there a rational basis to this or is it just a "leap of faith"? The early work of McIntyre (1980) and Humphreys (1981) examined these questions, but it hasn't yet affected the way we apply laboratory data to building standards. Certainly the role of clothing is one obvious influencing factor, since there is much greater variability in occupants' clothing patterns in real buildings, compared to the standard uniforms used in lab studies (as well as the single average clo value that might be chosen when using the PMV-based standards). If people dress merely for fashion, then random differences in clothing are likely to increase inter-individual differences (and increase the % dissatisfied) when a group is exposed to a single thermal environment. But if people dress in response to the expected indoor / outdoor climate, and to their own thermal sensitivities (i.e., are they typically warmer or cooler than other people), then the inter-individual differences would likely decrease (and the % dissatisfied decrease as well). In a study of office workers in Australia, Morgan (2000) found that corporate dress codes override thermal comfort considerations. We also know that women typically have a significantly more weather/season sensitive clothing response than their male counterparts in the office, so this creates two quite distinct subpopulations in terms of thermal insulation. The implications of this and other clothing behavioral issues for indoor climate management need further research.

<u>Climatic context.</u> It is clear that outdoor climate influences thermal perceptions beyond just the clothing that they wear. It clearly has a psychological effect on their expectations, particularly in naturally conditioned buildings that are more closely connected to the natural swings of the outdoor climate. The ACS was developed using mean monthly outdoor temperature as the input, because this would be one of the easiest for practitioners to use. However, an interesting question for researchers to continue to investigate is what other characterizations of the outdoor climate might be more highly correlated to people's perception of indoor comfort? Perhaps future studies can investigate parameters such as simultaneous outdoor temperature, daily average, some measure of daily range or peak conditions, a weighted measure of the recent history of temperatures over the previous few days or weeks, etc. And what about temperature forecasts? Do they influence clothing decisions too? While some of these questions have already been investigated (particularly noteworthy is Humphreys' (1979) examination of clothing insulation patterns as a function of weighted functions of outdoor temperature) there remains more work to do before such characterizations of climatic context become a regular part of researcher's analysis.

<u>The role of control</u>. An increasing number of people are accepting and even promoting the use of individual thermal control in buildings, either as operable windows, task/ambient conditioning systems, or other forms. The questions no longer center around "should we", but instead are focused on "how". Effort needs to be spent on developing new products and technologies, educating architects and engineers, documenting and reducing costs, and re-evaluating building fire codes that are often a significant barrier to incorporating such technologies. There are also many issues that thermal comfort researchers need to address, with the aim of providing alternative recommendations for acceptable thermal conditions when occupants themselves are able to control those conditions. In particular, previous studies have indicated that there is a difference between the effects of perceived control and utilized control (Paciuk, 1990). This has important implications for the design and operation of products, environmental control systems, and buildings.

Recent research (RP-843, Toftum, 2000) indicates quite persuasively that 28^{o}C is overwhelmingly preferable to 26^{o}C (with fixed airspeeds of 0.2 m/s) if the subject in the warmer environment is permitted to select their own preferred airspeed. In this scenario, higher temperatures would allow significant cooling energy savings in situations where you can utilize the outdoor air for cooling with natural ventilation, or even in an air conditioned spaces with task/ambient conditioning (w/ control of air movement), because more use can be made of the economizer cycle.

There is also evidence that the increased availability of personal control has positive effects far beyond just thermal comfort. Hawkes (1982) found that energy efficiency was actually improved when people were given control of their environment, because energy use was more closely allied to needs rather than maintaining uniformity based on externally-imposed standards. Wilson and Hedge (1987) found that fewer building-related ill health symptoms and greater productivity were achieved as the perceived level of individual control increased. Additional research has been done on this topic over the last decade and needs to be reviewed. The impact of personal control cannot be underestimated, but clearly needs to be investigated further so we can understand its impact on comfort, health, productivity, and energy use, and how we can best incorporate it into our buildings.

Beyond thermal neutrality. Thermal comfort standards, and mechanical engineers designing environmental control system, typically strive to provide neutral thermal conditions that are constant in time, and uniform throughout the environment. The goal is often to avoid the negative, and minimize dissatisfaction. Is it possible to move beyond this thinking? Is thermal monotony always a good thing? Kwok (2000) reviewed research and collected anecdotes regarding the concept of thermal monotony, or thermal boredom, in indoor environments. McIntyre (1980) made a early plea for counteracting thermal boredom with fluctuating interior temperatures to meet our inherent needs for sensory and stimulation.

Perhaps we should be aiming for a higher level of experiential quality in our environments, where “pleasantness” rather than “neutrality” are the goals (Kuno 1995). Can thermal qualities be used in a more purposeful way to add to the richness of our indoor environments? Can we create spaces that are more than neutral, where people can find “thermal delight”, where they can interact with their environments, and be refreshed and stimulated by them (Heschong 1979)? Perhaps this is too much to ask of a thermal comfort standard, but certainly appropriate to place in the minds of designers. For example, in situations of high density occupancy for sustained periods of 60 to 90 minutes (like a classroom) there is typically a steady temperature ramp that, while incrementally unnoticeable, can often give rise to widespread occupant discomfort towards the end of the exposure. In such situations it may well be appropriate to "flush" the occupied zone with periodic "bursts" of air from the mechanical ventilation system in a way that breaks thermal monotony and offsets mild but growing warm discomfort.

Beyond thermal comfort. Researchers need to take a more integrative view of the indoor environment. With few exceptions, most studies look at one outcome at a time, and try to assess what the ideal environmental conditions would be for optimizing thermal comfort, indoor air quality, energy consumption, or productivity. Is there a way to optimize them all simultaneously? Research findings often suggest conflicting goals for the indoor environment. For example, recent work has shown that perceptions of indoor air quality are improved when temperatures are cooler, and you can therefore decrease ventilation rates (Fang, 1999). But what are the energy implications of this finding? Although decreased ventilation rates would reduce energy consumption, cooler temperatures would either decrease or increase energy use, depending on whether you're in a heating or cooling situation. We have recently learned of the benefits of low enthalpy environments in terms of perceived indoor air quality, but what about elevated air speeds? Many practitioners report that the stillness of air within the occupied zone of most air-conditioned spaces (as mandated by current standards like ASHRAE Std 55) is associated with complaints of poor quality "dead" air. Perhaps elevated air speeds within the occupied zone can not only permit thermal comfort to be achieved at higher temperatures (thereby saving on refrigerated energy inputs), but also improve perceived air quality, or at least offset the enthalpy effect.

Many important thermal comfort questions still need answers, and a new generation of researchers need to be trained to provide them. In thinking beyond just thermal comfort, many people can easily agree on some of the more obvious recommendations for improved environmental control – reduce indoor pollution sources, deliver the air closer to the occupants, provide personal control where feasible. But tougher questions still remain. What are our objectives for conditioning the thermal environment? Is it better to provide air warmer or cooler than the "neutral" temperatures at the middle of existing standards? The answer may depend on context – are you trying to optimize comfort, indoor air quality, energy, productivity, or all of them? Is the budget the prime consideration or are environmental impacts of the building across its life-cycle also taken into account? Is it even reasonable to think that we can create a single environment that optimizes all these outcomes for all people? Probably not. Perhaps the most appropriate goal would be to provide a <u>variety</u> of means for people to control their own environment. As examples, this could range from a workplace culture that allows a flexible dress code and policy for taking breaks, to providing means for control of the local physical environment (TAC, windows, local controls, etc.), or providing areas within the building that have different thermal conditions.

One clear conclusion seems to emerge - the "one-size-fits-all" and "uniform conditioning" approach to indoor climate management is fast becoming a curious but misguided fad of the last century.

Acknowledgments

We extend our warm gratitude to ASHRAE for funding this research, to the many researchers around the world who generously donated their raw field data, to Donna Cooper of Macquarie University for her work on the database and original statistical analysis, and to David White of University of California, Berkeley for his additional statistical analysis.

References

ASHRAE, 1992, *Standard 55 - Thermal Environmental Conditions for Human Occupancy*. Atlanta, ASHRAE Inc.

ASHRAE, 1995, *Addendum to Standard 55 - Thermal Environmental Conditions for Human Occupancy*. Atlanta, ASHRAE Inc.

Bauman, F.S., T.G. Carter, A.V. Baughman, and E.A. Arens (1998), "Field Study of the Impact of a Desktop Task/Ambient Conditioning System in Office Buildings." *ASHRAE Transactions,* Vol 104 (1).

Brager, G. S.; and de Dear, R. J. (1998), "Thermal Adaptation in the Built Environment: A Literature Review", *Energy and Buildings*, V.27(1), p.83-96.

Brager, G.S., and de Dear, R.J (2000), "A Standard for Natural Ventilation", *ASHRAE Journal*,Vol 42, no. 10, pp. 21-28.

de Dear, R.J., G.S. Brager and D.J. Cooper (1997), *Developing an Adaptive Model of Thermal Comfort and Preference – Final Report, ASHRAE RP-884*. Sydney:MRL.

de Dear, R.J. (1998), "A Global Database of Thermal Comfort Field Experiments." *ASHRAE Trans.*, V.104(1b), p.1141-1152.

de Dear R.J.and G.S. Brager (1998), "Developing an Adaptive Model of Thermal Comfort and Preference", *ASHRAE Transactions*., V.104(1a), p.145-167

Fang, L., Wargocki, P., Witterseh, T., Clausen, G., Fanger, P.O. (1999), "Field Study on the Impact of Temperature, Humidity and Ventilation on Perceived Air Quality. "*Proceedings of Indoor Air'99, Edinburgh, Scotland,* V.2, pp.107-112.

Fanger, P.O. (1970), *Thermal Comfort - Analysis and Applications in Environmental Engineering*. (Copenhagen: Danish Technical Press).

Hawkes, D. (1982), "The Theoretical Basis of Comfort in the Selective Control of Environments" *Energy and Buildings* 5: 127-134.

Heschong, L. (1979), *Thermal Delight in Architecture*, Cambridge, MA. MIT Press.

Humphreys, M.A. (1978), "The Dependence of Comfortable Temperatures upon Indoor and Outdoor Climates", *Bioengieering, Thermal Physiology and Comfort*, (eds Cena and Clark). London, Elsevier.

Humphreys, M.A. (1979) "The Influence of Season and Ambient Temperarture on Human Clothing Behaviour.", *Indoor Climate* (ed., Fanger and Valbjorn), Danish Building Research Institute; Copenhagen. pp.699-714.

Kuno, S. (1995). "Comfort and Pleasantness". *Pan Pacific Symposium on Building and Urban Environmental Condition*, Nagoya, Japan.

Kwok, A. (2000). "Thermal Boredom". *Plea*: July 2-5, Cambridge, England.

McIntyre, D.A. 1980. *Indoor Climate*. London: Applied Science Publishers, Ltd.

Morgan, C. (2000) *The Role of Clothing in Climatic Adaptation*. Unpublished MSc thesis, Macquarie University, Sydney.

Olesen, B.J. (2000). "Guidelines for Comfort". *ASHRAE Journal*, vol 42, no. 8, pp.41-46.

Paciuk, M.(1990), "The Role of Personal Control of the Environment in Thermal Comfort and Satisfaction at the Workplace". *Coming of Age*, Environmental Design Research Association 21: 303-312.

Schiller, G.; Arens, E.; Bauman, F.; Benton, C.; Fountain, M.; Doherty, T. (1988), "A Field Study of Thermal Environments and Comfort in Office Buildings", *ASHRAE Transactions*, Vol. 94, Part 2.

Toftum, J., Melikov, A.K., Rasmussen, L.W., Kuciel, A.A., Cinalska, E.A., Tynel, A., Bruzda, M., Fanger, P.O. (2000). *Human Response to Air Movement – Part I : Preference and Draft Discomfort*. (DTU International Centre for Indoor Environment and Energy: Denmark).

Wilson, S. and A. Hedge. (1987), "The Office Environment Survey: a Study of Building Sickness". *Building use studies*, May 1987.