ADAPTIVE THERMAL COMFORT IN NATURAL AND HYBRID VENTILATION

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ABSTRACT

Current thermal comfort standards and the models underpinning them purport to be equally applicable across all types of buildings, ventilation systems, occupancy patterns, and climate zones. A recent ASHRAE-sponsored research project (RP-884) critically evaluated this by statistically analysing a large thermal comfort field research database from 160 buildings scattered all over the would (n=22,000). The results suggest several significant changes for the next revision of ASHRAE's comfort standard (ASHRAE Std 55), particularly as they relate to buildings with natural and hybrid ventilation systems.

1. INTRODUCTION

The oil shocks of the 1970s prompted close scrutiny of building thermal insulation and air-tightness of building envelopes to decrease energy consumption for Heating, Ventilating and Air-Conditioning (HVAC). Buildings were deliberately sealed off from their outdoor environment. Indoor environments were very rigidly automated with artificial lighting, mechanical ventilation and heating and cooling systems. These developments necessitated some rational basis for engineering and managing indoor climate and ensuring thermal comfort for building occupants who, by the nature of their tightly regulated buildings, were completely excluded from playing an active rôle in achieving thermal comfort. Thermal comfort standards have therefore aimed to fulfil that need, with their rationale being to optimize the thermal acceptability of indoor environments. Recognising the impossibility of keeping *everybody* happy *all* of the time within a single set of environmental conditions, the stated intention of comfort standards is simply to minimize the number of dissatisfied occupants. To that end, the conventional "comfort wisdom" embodied in these standards (ASHRAE 1992, ISO 1994) prescribes an envelope of thermal conditions to be applied uniformly through indoor space and time. In practice, however, engineers very typically opt for a set of design conditions of cool, still air falling somewhere near the middle of the Summer and Winter charts depicted in Figure 1.

Standards like ASHRAE 55 are derived from a "static" model of thermal comfort that views occupants as passive recipients of thermal stimuli. In this model subjective states are regarded purely as functions of the physics of the body's thermal balance with its immediate environment, as mediated by autonomic physiological responses. These biophysical relationships are assumed to be *universally applicable across all* building types, *all* climate zones, and *all* populations (eg. Parsons 1994). But many researchers are beginning to critically question and test this universality, arguing that it ignores significant cultural, climatic, social and contextual dimensions of comfort, leading to an exaggeration of the "need" for refrigerated cool, still air (Kempton and Lutzenhiser 1992, Prins, 1992; Brager and de Dear, 1997).

The closing decades of the 20th century have witnessed growing public disquiet over the prodigious energy inputs to buildings that slavishly implement the "static model" of thermal comfort. Of particular concern are the global environmental impacts such as greenhouse warming caused by mismanagement of energy resources within the built environment. The architectural and engineering responses to these concerns include optimal use of sustainable

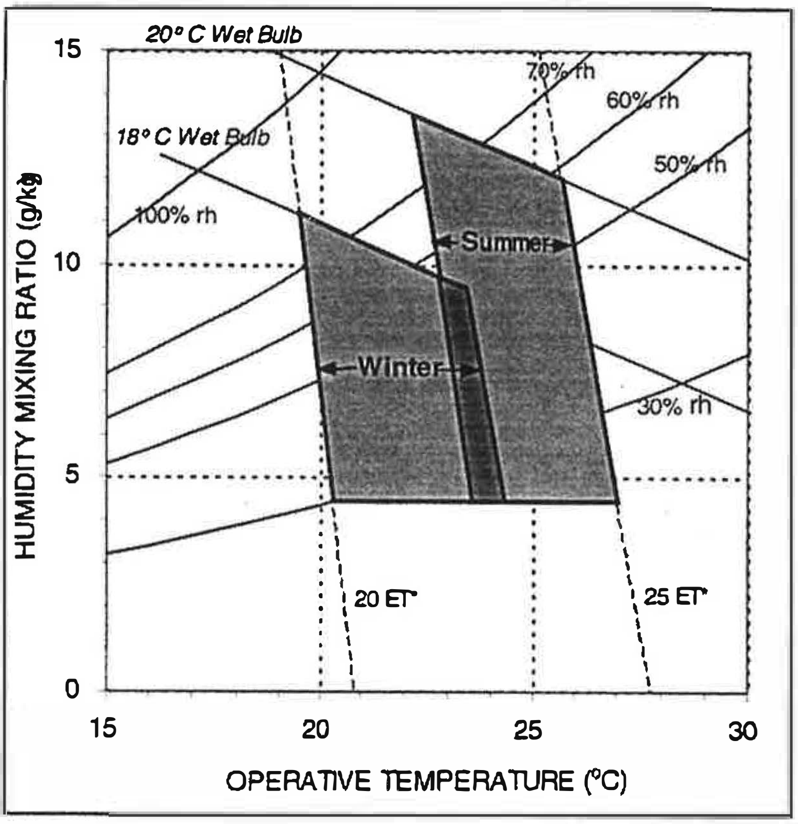

Figure 1: ASHRAE Standard 55-92: Thermal environmental conditions for human occupancy.

technologies such as passive solar gains, daylight and natural ventilation – all falling under the rubric of "bioclimatic design" (Szokolay, 1998). However, these "environmentally responsible" ideals are fundamentally inconsistent with "conventional comfort wisdom" (cool, still air) and have therefore prompted calls for alternative strategies such as a *variable indoor temperature standard* to supplement the current ASHRAE Standard 55 (1992). A variable indoor temperature standard, based on the adaptive model of thermal comfort, has particular relevance to naturally ventilated buildings, buildings with hybrid ventilation systems, and other situations in which building occupants have some degree of indoor climatic control. In the case of hybrid systems such a standard could offer guidance to designers and facilities managers in relation to those critical thresholds when the building switches between passive and active modes of indoor climate control.

A variable temperature standard links indoor temperatures to the climatic context of the building, and accounts for past thermal experiences and current thermal expectations of their occupants. An important premise of the adaptive model is that building occupants are no longer regarded as passive recipients of the thermal environment, as in the case of climate chamber experimental subjects, but rather, play an *active* rôle in creating and fulfilling their own thermal preferences. Contextual factors and past thermal history are believed to modify expectations and thermal preferences. Satisfaction with an indoor climate results from matching actual thermal conditions in a given context and one's thermal expectations of what the indoor climate *should* be like in that same context (Auliciems 1981, 1989, de Dear 1994, Nicol 1993). In short, satisfaction occurs through appropriate adaptation to the indoor climatic environment.

This paper reports results from the ASHRAE RP-884 project - *Developing an Adaptive Model of Thermal Comfort and Preference.* The research was premised on the development and analysis of a quality-controlled, cumulative database of thermal comfort field experiments worldwide (see de Dear 1998 for more details on the RP-884 database). The analysis was intended to critically question the conventional comfort wisdom embodied in current thermal comfort standards. While the project looked at both air-conditioned and free running buildings, its findings have particular relevance to natural and hybrid ventilation strategies which are the focus of this meeting

2. METHODS

ASHRAE is fully cognizant of the limited empirical bases of its comfort standard. Documents like Standard 55 were intended for routine use by HVAC engineers and facilities managers but these end-users have often expressed concerns about the validity of generalising from simplistic laboratory studies on small samples of college students to the global population of building occupants. In response to these concerns, ASHRAE's Technical Committee in charge of Standard 55 (TC 2.1) initiated a program field validation experiments in various climate-zones ranging from Mediterranean, through hot-humid and hot-dry zones to cold continental. Thousands of building occupants going about their normal day-to-day activities have volunteered their perceptions of the thermal environment inside their buildings. Mindful of the common criticisms levelled at research in the field, the Technical Committee in charge this research program specified laboratory-grade instrumentation and meticulous compliance with the procedures set out in Standard 55. An example of the type of indoor-climatic instrumentation developed for this field program is depicted in Figure 2 (Cena and de Dear, 1999). Bare essential sensors must measure air and radiant temperatures, humidity and air speed. Apart from standardised instruments, the ASHRAE program has also defined a standard field questionnaire and protocol – as a bare minimum, thermal comfort questionnaires now require the ASHRAE 7-point sensation scale, and a clothing garment check-list, a metabolic rate check-list, all to be administered at the same time/place as the indoor climatic instrumentation is being used.

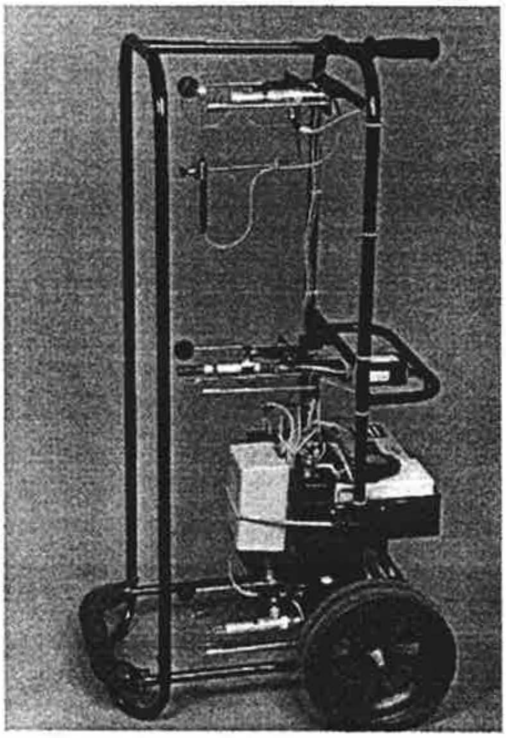

Figure 2: field study instrumentation (Cena and de Dear, 1999)

2.1 Quality-Controlled Database of Thermal Comfort Field Research

Since its inception in the 1980s, ASHRAE's field research program has become the *de facto* methodological model and numerous independent researchers have since adopted and applied it in their respective parts of the world. The RP-884 project that is the subject of this paper assembled a database of such results by sending a three-page questionnaire on field research methods to most of the thermal comfort research community currently or recently active in field research. On the basis of the questionnaire returns, raw field data were requisitioned from researchers whose:

- measurement techniques, both physical and subjective, approximated "laboratory-grade,"

- data structures allowed each set of questionnaire responses to be linked to a concurrent set of indoor and outdoor climate observations, and
- indoor climatic observations were comprehensive enough to enable heat-balance indices such as *PMV* and *ET** (the "static model") to be calculated for each questionnaire respondent.

A primary goal was to keep the internal consistency of the database as high as possible. To this end, the RP-884 team requisitioned raw field data files instead of processed or published findings, enabling the application of a variety of quality controls and standardised data processing techniques. Since the database is described in detail in de Dear (1998), the purpose of the next section is to briefly outline its contents and the basic steps taken to ensure its integrity. A total of 160 different buildings were included. The database has been put in the public domain and is readily available to the comfort research community at http://atmos.es.mq.edu.au/~rdedear/ashrae_rp884_home.html.

The raw data comprising the RP-884 database came from four continents and a broad spectrum of climatic zones. Nearly 22,000 sets of raw data were compiled from several locations in England and Wales, Bangkok Thailand, several Californian locations, Montreal and Ottawa in Canada, six cities across Australia, five cities in Pakistan, Athens in Greece, Indonesia, Singapore, and Grand Rapids in Michigan .

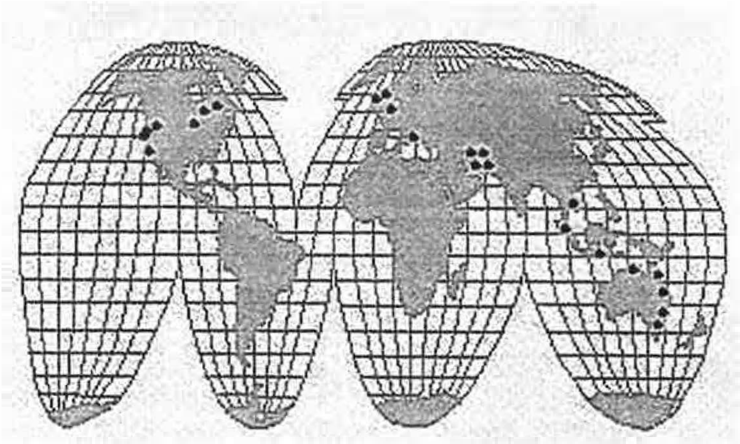

Figure 3: The geographic spread of building studies comprising the RP-884 thermal comfort database

Each complete set of raw data was structured within the database using the template developed in previous ASHRAE-funded research projects, particularly RP-462 (Schiller *et al.* 1988). The data fields included: a) thermal questionnaire responses (sensation, acceptability, preference), b) calibrated clothing and metabolic estimates, c) concurrent indoor climate measurements (air and globe temperatures, air velocity, dewpoint, plane radiant asymmetry temperature), d) calculated thermal indices based on the standard software package known as *WinComf*© by Fountain and Huizenga, (1996), and e) outdoor meteorological observations including daily temperatures and relative humidity at 600 hours and 1500 hours.

After each raw field data file was quality controlled and standardised into the template it was broken down according to season (summer/winter) and building type (centrally-controlled buildings - HVAC), naturally ventilated buildings (NV), and mixed-mode buildings. The classification of buildings largely depended on the judgment of the original researchers supplying raw data, but the main distinction between centrally-controlled HVAC and naturally ventilated buildings was that individual occupants in the former had little or no control over their immediate thermal environment, while occupants in naturally ventilated buildings at least had access to operable windows. It should be pointed out that most of the naturally ventilated buildings were only studied in the summer, and so the type of heating system was irrelevant. The few that were studied in winter may still have had a heating system in operation, but it was of the type that permitted occupant control. The sample included too few mixed-mode buildings to permit meaningful analysis, so the remainder of this paper refers exclusively to NV and HVAC buildings.

2.2 Meta-Analysis

The statistical analysis underlying the adaptive models was conducted at the scale of individual buildings, of which there were 160 in the database. In effect the modelling exercise can be thought of as a meta-analysis of the separate statistical analyses conducted on each of the 160 buildings within the database. Derived statistical products such as buildings' thermal neutralities (temperature corresponding with a mean thermal sensation vote of "neutral") and preferred temperatures were appended as new variables in the meta-file, but if the model or statistic in question failed to reach significance at $p<0.05$, the building registered a missing value code for that particular variable in the meta-file. The effect of this significance criterion was to eliminate from further analysis those buildings that had small sample sizes or very homogenous indoor climates.

In addition to *observed* neutralities for each building, the meta-file also contained neutralities *predicted* by Fanger's (1970) *PMV* heat-balance index. The method consisted of inputting each building's mean values for each of the five *PMV* variables (t_o, *rh, v,* I_{cl}*+chair insulation, met*) to the *WinComf*® software (Fountain and Huizenga, 1996). The *PMV* model was then solved iteratively by adjusting t_o (t_a with t_r linked) until the *PMV* output field equalled zero.

3. RESULTS AND DISCUSSION

The full data analysis in RP-884 has been presented in depth elsewhere (de Dear and Schiller Brager, 1998) so I will focus on those aspects most relevant to natural and hybrid ventilation.

The first and most obvious manifestation of adaptation to indoor climate is clothing behaviour, and this has been quantified in Figure 4. The much narrower range of indoor temperatures between 21 and 25°C in the HVAC part of the database (left panel of Figure 4) limited the range of clothing response in those contexts, as indicated by the weak correlation (explained variance = 18%). This point is emphasised by comparison with the naturally ventilated buildings (explained variance = 66%) on the right-hand side of Figure 4.

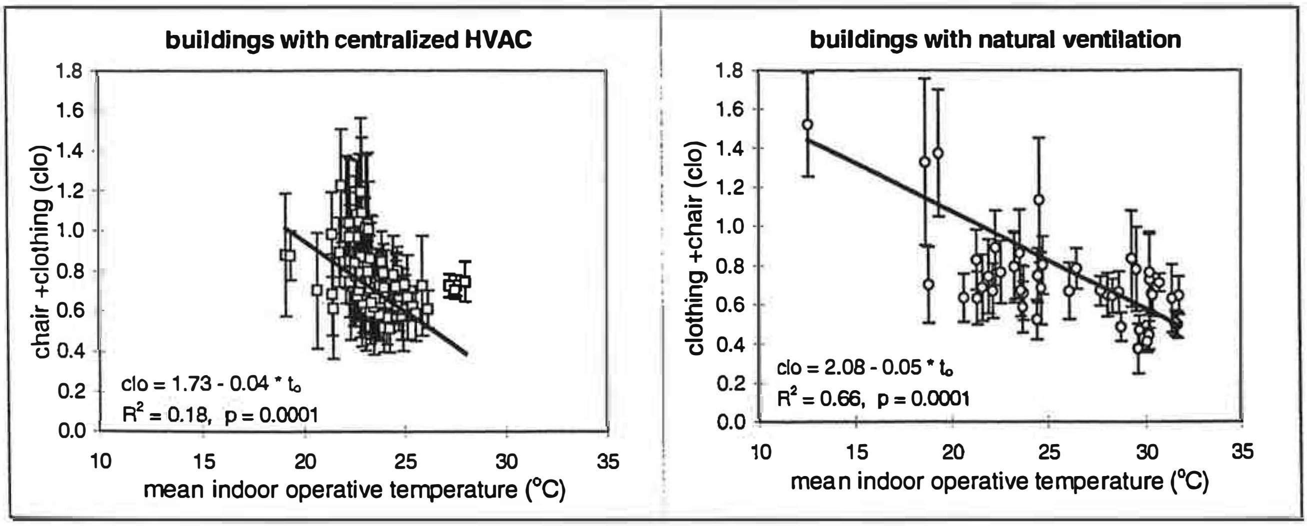

Figure 4: Clothing as an indicator of behavioural adaptation. Dependence of mean (± stdev) thermal insulation (clothes and chair) on mean indoor operative temperature

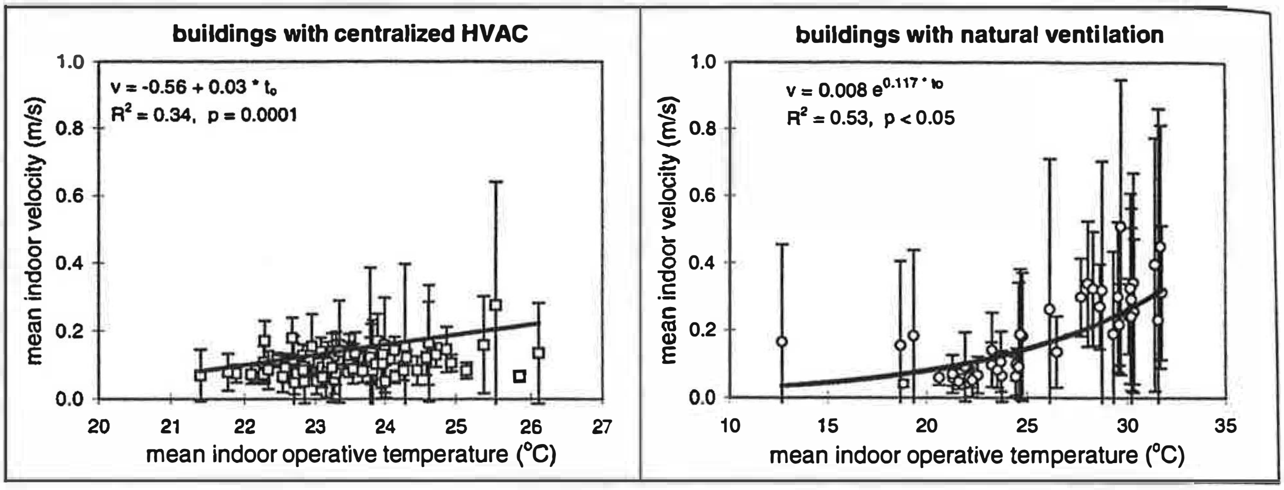

Figure 5: Air Velocity as an indicator of behavioural adaptation. Dependence of mean (± stdev) indoor air speeds on mean indoor operative temperature.

Air speeds within naturally ventilated spaces are one of the main mechanisms for maintaining acceptable thermal comfort in natural and hybrid ventilated spaces, but the current standards of thermal comfort such as ASHRAE's 55-92 limit permissible indoor air speeds to just 0.2 m/s. This limit corresponds to an average indoor operative temperature in the naturally ventilated spaces in the right hand panel of Figure 5 of about 26°C. Literal interpretation of the ASHRAE standard (or its ISO counterpart) limits us to the "cool, still air" approach to indoor climate.

The preceding analyses of clothing and indoor air speed indicate that the occupants of naturally ventilated spaces are behaviourally more responsive to their buildings' indoor climates than their counterparts in centralised HVAC buildings. This finding was also borne out in the analysis of subjective thermal comfort states such as thermal neutrality and preference (see de Dear and Schiller Brager 1998 for more details). It was noted that the indoor temperatures found to be neutral (ie. subjects voting zero on the seven-point scale sensation scale) were significantly warmer in locations with warm outdoor climates than they were in cold climate zones.

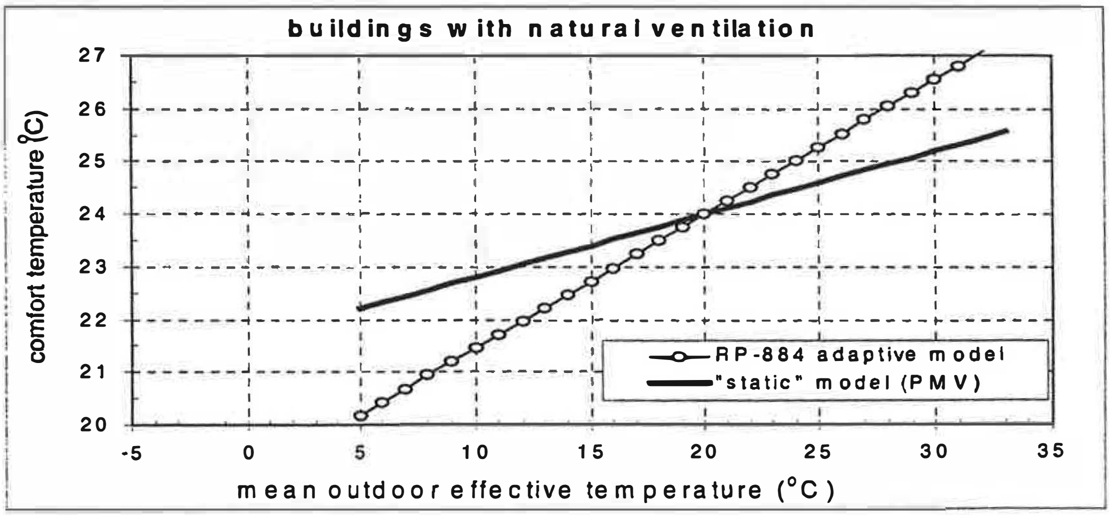

Figure 7: Adaptive *vs.* Static comfort model predictions. Comparison of the RP-884 adaptive models' predicted indoor comfort temperatures with those predicted by the "static" PMV model. The static model's comfort temperature for each building was derived by inputting the building's mean v, rh, clo, met into the PMV model and then iterating for different t_o until PMV=0.

More important than neutral sensation votes are expressions of thermal preference. The RP-884 analysis found the indoor temperatures that elicited a minimum number of requests for warmer or cooler conditions were, like thermal neutralities, a function of temperatures prevailing outside the building at the time of the survey. These *observed* results have been plotted in Figure 6 along with the optimum temperatures *predicted* by the "static model" (*PMV*) for all naturally ventilated buildings in the database. The clear dependence of thermal preferences on outdoor climate is the first point to note in Figure 6. Secondly, even though the *predicted* temperature optima (*PMV*) took account of the downward adjustments in clothing and upward adjustments in air speeds in the warmer climate zones, the predictions fell well short of the actually observed optimum temperatures. This can be interpreted as indicating that simple physical adjustments to clothing and air speed are insufficient to account for the shifting thermal perceptions in naturally ventilated buildings. Clearly we have to look beyond the physics of body heat-balance to explain these effects, and "thermal expectation" seem to be a plausible candidate. Occupants of such buildings appear to be fully cognizant that they are *not* air conditioned, and as a result, relax their thermal expectations accordingly so that variable indoor temperatures become the norm and are perfectly acceptable – or indeed in the case of Figure 6, preferable.

The relationship between observed optimum indoor temperature and outdoor temperature forms a rational basis of a variable temperature standard for exclusive use in buildings with natural and hybrid ventilation systems. Before it can be widely implemented, though, it needs the outdoor climatic term to be expressed in something a little more familiar to the practitioner than effective temperature (*ET**). Figure 7 re-plots the data in relation to outdoor air temperature (average of mean daily max and min). Also plotted are the ranges of temperatures found to correspond with thermal acceptability ratings of 90 and 80% It should be noted that these ratings were not derived from empirical acceptability questionnaire items. Instead they came from a commonly accepted relationship between mean thermal sensation vote (Fanger's *PMV*) and thermal dissatisfaction (Fanger's *PPD*) applied to the mean thermal sensation (ASHRAE vote) recorded in the RP-884 databases' buildings. The result indicates that a latitude of about one-and-a-half degrees either side of the optimum temperature is consistent with the maintenance of acceptable indoor climates in these naturally ventilated buildings.

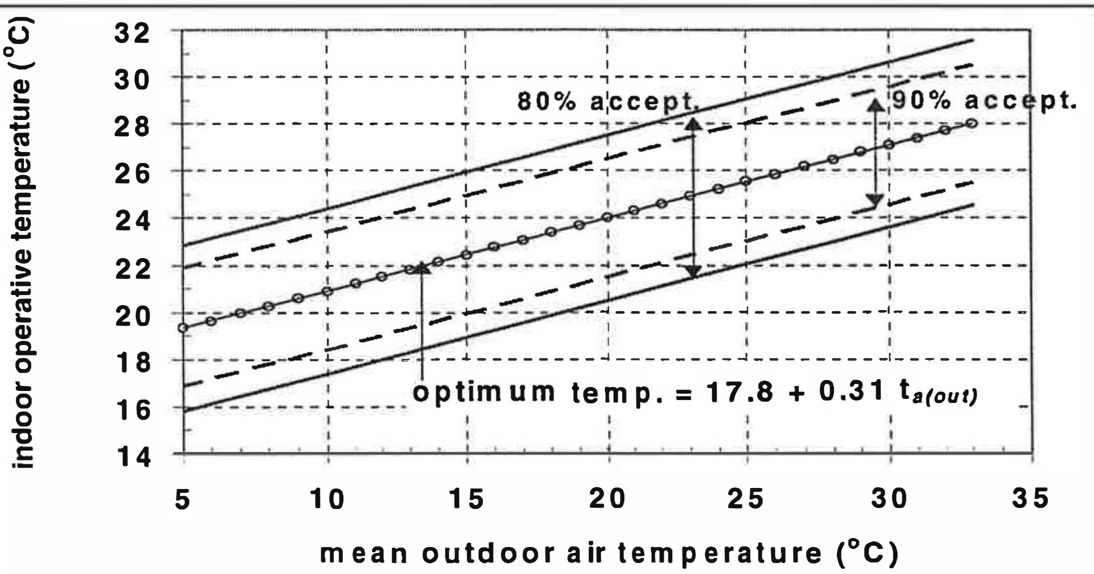

Figure 6: Optimum temperatures in naturally ventilated spaces as a function of prevailing outdoor temperature. $t_{a(out)}$ is simply an arithmetic average of the mean monthly minimum and maximum dally air temperatures for the month in question.

4. CONCLUSIONS

A clear implication of the adaptive model of thermal comfort, as represented in Figure 7, is that indoor temperatures failing the so-called "static model" of comfort (as in ASHRAE's Standard 55-92 , see Figure 1 of this paper) may still be acceptable or even preferable within buildings with natural or hybrid ventilation systems. That is – the "cool, still air" approach to thermal comfort is unduly restrictive in such buildings and, as such, should not be regarded as the appropriate criterion when decisions are being made about whether or not to install centralized HVAC systems. If a design can be shown to achieve indoor temperatures within the much broader adaptive range depicted in Figure 7, at the appropriate season, a *prima facie* case exists for ***not*** resorting to conventional air-conditioning solutions, unless other non-thermal factors dictate otherwise. If nothing else the RP-884 project has demonstrated that Standard 55-92, in its present form at least, is not relevant to a large part of the building stock across a large swathe of global climatic regions. Therefore the Standard needs to have its scope explicitly narrowed down to those situations for which it was originally intended – namely, buildings with large numbers of occupants who have no individual control over their indoor climates. Or even better, a new section dealing with the special requirements of natural and hybrid ventilation needs to be inserted in the next revision of Standard 55.

The "static model" protagonists' traditional, and increasingly strident rebuttal of the adaptive comfort model has focused on the methodological shortcomings of field research. In particular, inadequacies of instrumentation, or omission of key data like clothing insulation or metabolic rates. The ASHRAE RP-884 project's delivery of an empirically defensible adaptive model of thermal comfort, based on an enormous volume of quality-controlled field observations, has necessitated a shift in emphasis by its critics. Their new strategy has been to highlight either draft risk or air quality reasons for eschewing variable indoor climates and bioclimatic designs. The idea of draft risk in warm and naturally ventilated environments has found no empirical support outside Scandinavian climate chamber studies, and so does not need to be dealt with here. However the air quality argument is new and as such, deserves closer scrutiny. In particular we are seeing a renewed emphasis on the role played by enthalpy in overall indoor air quality (e.g. Fanger, 1998). Danish laboratory studies indicate that subjective assessments of indoor air quality deteriorate in environments with elevated temperature, humidity, or both. By rather direct implication, the uncontrolled, or at least partially deregulated indoor climates being advocated in this paper must, *ipso facto*, have unacceptable indoor air quality. But before accepting studies based on a handful of college-age Danish paid subjects and uncritically extrapolating their conclusions to occupants of every built environment across the rest of the world, we should familiarise ourselves with the extensive IAQ *field* literature, especially as it relates to the Sick Building Syndrome (SBS). Mendell's (1993) review of several very large SBS field studies found consistently higher symptom prevalence in conventionally air-conditioned as opposed to naturally ventilated buildings. In another document representing possibly the most extensive literature review of SBS field studies to date, Raw at the British Research Establishment noted that the lowest [SBS] symptom prevalence in the UK was always found in naturally ventilated buildings and mechanically ventilated [without refrigerated cooling] buildings. "Mean levels [of SBS symptom prevalence] are *clearly higher* where there is cooling capacity in the ventilation system, but only a small additional risk appears to be present where there is humidification" (Raw, 1992, p.17). These generalisations from very large numbers of *real* building occupants inside *real* buildings performing *real* occupations cannot be so readily dismissed in favour of a handful of responses from paid college-age subjects with their noses inserted in IAQ "sniffing ports."

The weight of research evidence to date suggests that neither the "risk" of draft nor the possibility of negative indoor air quality posed by elevated enthalpy in buildings with natural or hybrid ventilation systems are real enough to sacrifice the environmentally sustainable goals of bioclimatic design strategies.

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