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Field Research Results and ASHRAE Standards - Do They Conflict?

Researchers at the University of California, Berkeley, found that at "optimal" thermal comfort conditions (around 72.5°F or 22.5°C), 12% of office occupants surveyed were nonetheless uncomfortable with their thermal environment. This compares with only 5% predicted by equations from models based on laboratory studies.

The researchers also found that far more of the study building occupants were uncomfortable at temperatures near the upper end of the comfort range than predicted by the models. At temperatures of 78°F (25.5°C), more than 35% of the study occupants were uncomfortable. The models predicted that only 20% would be uncomfortable at 80°F (26.7°C) whereas nearly 50% of the study subjects were uncomfortable when the temperatures got that high.

At the lower end of the temperatures studied, the building occupants were less uncomfortable than predicted by one of the models and more than predicted by another. Overall, the study subject responses indicate that an optimal temperature is about 72.5°F (22.5°C) rather than the 76°F (24.5°C) predicted by the models. Both the ASHRAE thermal comfort standard, Standard 55-1981, and ISO thermal comfort standards are based on these same models that are derived from laboratory studies. They provide guidelines based on satisfaction of no less than 80% of building occupants.

These standards are the basis for modern building design in most of Europe and North America. Therefore, the study's findings raise important questions for architects, engineers, and building operators:

What is an optimal thermal environment?

What is an acceptable level of dissatisfied occupants?

If the standards are unreliable, what guidelines should designers follow?

Thermal Comfort

Virtually everyone concerned with building environmental conditions is familiar with ASHRAE's thermal comfort envelope, which is the portion of the psychrometric chart where people should be comfortable. The basis for the chart is a wealth of very careful laboratory studies done in the United States and in Europe. Figure 1 shows our version of ASHRAE's thermal comfort envelope.

Thermal comfort preferences vary significantly from one person to another. Age, gender, and other physiological differences all affect individual preferences. Even at near-optimal effective temperatures (ET*, as defined by either laboratory or field studies), some occupants will be too cold while others are too warm. These differences are hard for building designers and operators to control or predict. Individuals themselves control the more important factors of activity and clothing; laboratory studies cannot anticipate these variables.

Thermal sensations are produced by heat transfer to the environment and the resulting body temperatures and physiological adjustments. Environmental and personal factors govern the heat transfer. The environmental factors are air temperature, thermal radiation, air movement,

Inside This Issue:

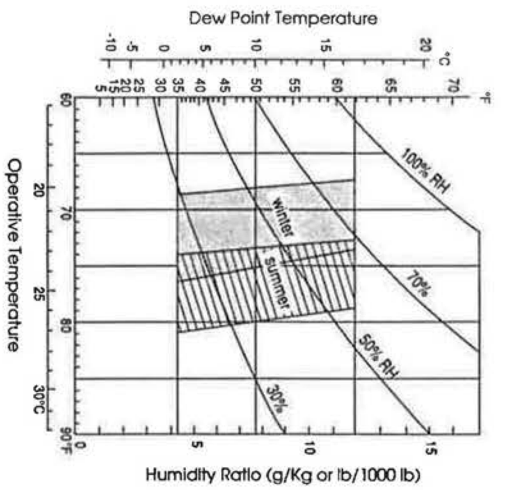

Figure 1 - ASHRAE Thermal Comfort Envelopes for Summer and Winter.
Redrawn by ***IAB*** and based on Standard 55-1981.

and humidity. The personal factors are individual physiology, activity, and clothing. David Wyon of Sweden, who has conducted many studies of thermal comfort, says that when are bodies are not in thermal neutrality, we get sick. (See ***IAB***, Vol. 1, No. 7 and Vol. 2, No. 1)

Thermal comfort is a subjective evaluation based on thermal sensations. Attitudes based on prior experience and current expectations affect how an individual registers and evaluates these sensations. Figure 2 shows a "two-way linked-chain" sequence for how the environment affects the thermal comfort experience. Note that this is a two-way cause-and-effect interaction; a feedback loop affects the factors on each side. Some of these interactions are conscious and others are autonomic responses that include the nervous, respiratory-circulatory, endocrine, and musculo-skeletal systems. Others require active intervention such as changing thermostat settings, window openings, clothing, or activity levels. While the importance of the variables in Figure 2 is widely recognized, the recent field research suggests that we may not adequately understand them.

UC Berkeley Field Study

The field study involved ten buildings with 2,342 visits to 304 workers in the San Francisco Bay Area. The work is reported in several articles referenced at the end of this one. Each office worker completed a 53 data-field thermal assessment survey addressing thermal sensation, thermal preference, comfort, mood, clothing, and activity. The survey used a six-point general comfort scale with 1, 2, and 3 equal to very, moderately, and slightly uncomfortable, and 4, 5, and 6 equal to slightly, moderately, and very comfortable respectively.

After filling in the survey, workers stepped away from their desks and mobile instrumentation was used directly at the workstations to characterize the thermal environment. Measurements included air temperature, dewpoint temperature, globe temperature, air velocity, radiant temperature asymmetry, and illuminance.

Researchers based thermal sensation predictions on two models, one by Fanger and one by Gagge (see references for more details). Fanger developed the commonly used index of Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD). PMV predicts the thermal comfort responses of a large group of people exposed to the same thermal conditions. The voter used the seven-point ASHRAE Thermal Sensation Scale shown in Figure 3.

PPD is the predicted percentage of people who will express dissatisfaction with a given thermal environment. Dissatisfaction is assumed if the votes are either warm or hot (vote = 2 or 3) or cool or cold (vote = -2 or -3). Figure 4 shows the PPD distribution of a theoretical group of PMV votes.

Gagge developed a modified version of PMV called PMVg by Brager. It differs only in its treatment of dry heat transfer from the skin that is calculated from Gagge's

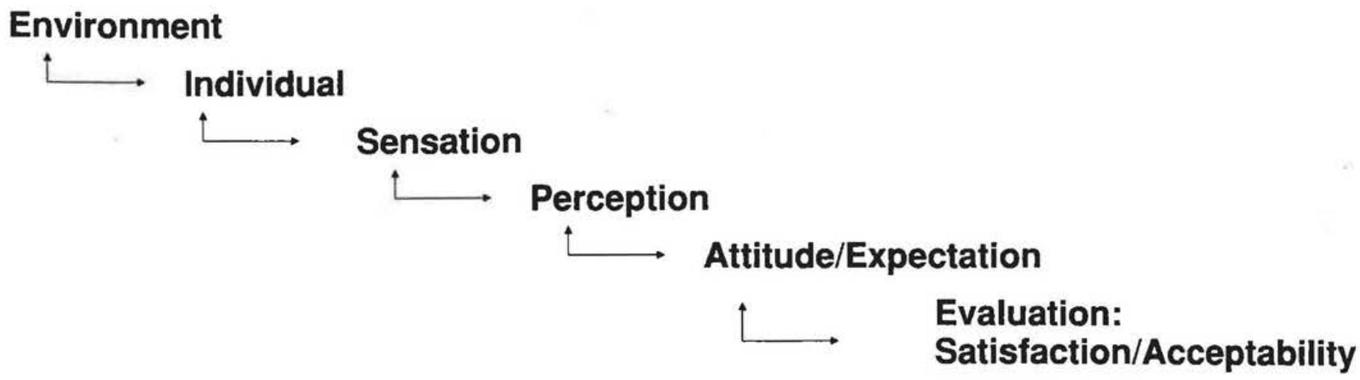

Figure 2 - Two-way Linked-chain Sequence of Environment/Human Thermal Comfort Interactions.

+3 . . . . . Hot
+2 . . . . . Warm
+1 . . . . . Slightly warm
0 . . . . . Neutral
-1 . . . . . Slightly cool
-2 . . . . . Cool
-3 . . . . . Cold

Figure 3 - ASHRAE Thermal Sensation Scale.
Developed by Fanger and used in many studies including the University of California field study.

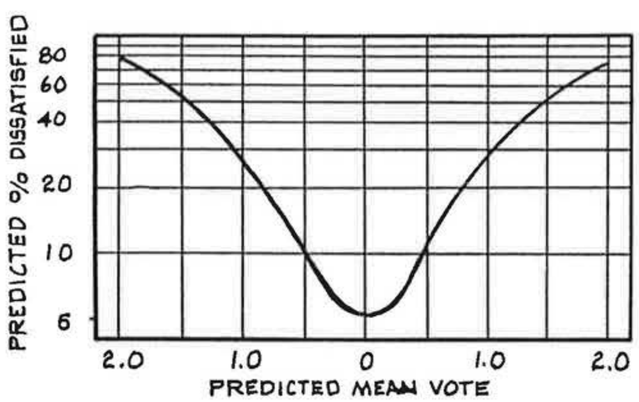

Figure 4 - Predicted Percentage of Dissatisfied (PPD) as a Function of Predicted Mean Vote (PMV).
Redrawn from *ASHRAE Handbook: Fundamentals* (1989).

own "two-node" model rather than from Fanger's empirically derived equation based on thermal neutral sensation at a given activity level. Figure 5 shows Brager's graph re-drawn by ***IAB***. The graph originally appeared in the April 1992 *ASHRAE Journal.*

Findings

Thermal comfort conditions are expressed as Effective Temperature (ET*) and are determined by a complicated mathematical expression that includes air temperature, surface radiant temperature, air movement, and relative humidity. Neutral temperature is the theoretical optimum where the least number of people is likely to experience thermal discomfort. It's determined by either measurement or mathematical models. Table 1 shows the study's results compared to the predicted values based on the Fanger and Gagge models.

Figure 5 shows a plot of the field study results and two of the more important equations based on the laboratory research. According to Brager, the Fanger and Gagge models both overestimate the optimal temperature by about 2°F (5°C) compared with the University of California field measurements. At the optimal temperature, they underestimate the percentage of occupants who will be uncomfortable by more than a factor of two. Brager and her colleagues' measurements indicate that 12% of the individuals would be dissatisfied at the optimal temperature of 74.3°F (23.5°C). This compares to the Fanger and Gagge models' 5% predicted dissatisfied.

The models underestimate the amount of dissatisfaction at warmer temperatures. The Fanger model severely underestimates the number of people who would be dissatisfied with temperatures above 76°F (24°C). Of particular interest is the very high level of dissatisfaction, around 50%, at the extremes of the ASHRAE comfort envelope. This raises troubling questions if it represents office workers generally. Can it be that workers in the San Francisco Bay Area are different from most other workers? Some people would quickly say yes - facetiously, we hope. However, the study subjects were typical and their office environments similar to those of their counterparts elsewhere.

Why the Discrepancies?

Why don't the Berkeley results agree with the predictions made by the models based on laboratory studies?

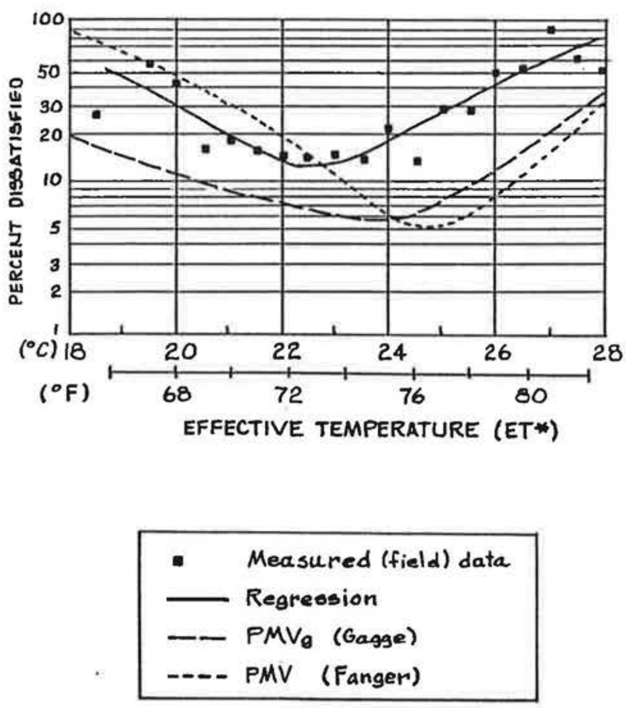

Figure 5 - Percent Dissatisfied versus ET*.
Redrawn from Brager (1992).

Neutral Temperature	Winter	Summer
Measured	22.0°F	22.6°F
PMV Predicted	24.4°F	25.0°F
PMVg Predicted	23.6°F	24.0°F
Neutral averages used for predictions		
Air temperature	22.8°F	23.3°F
Mean radiant temperature	23.0°F	23.6°F
Velocity	0.06 m/s	0.10 m/s
Clothing	0.58 clo	0.52 clo
Activity	1.12 met	1.14 met
Values required to match PMV-predicted and measured neutral temperatures		
Clothing	0.80 clo	0.72 clo
Activity	1.75 met	1.75 met

Note: a 0.06 m/s = 12 fpm; 0.10 m/s = 20 fpm.

Table 1 - Neutral Temperatures: Measured and Predicted.

According to the researchers, there are several possible explanations. One raised by both Ole Fanger and David Wyon was that the laboratory studies use wire chairs. These chairs are used to expose the subject's entire body without insulation from the chair itself.

However, typical office chairs do not expose the occupant to as much air and they also insulate; this may help explain why the laboratory studies found higher temperatures acceptable. David Wyon of Sweden commented that the chair could insulate 20 to 25% of the body surface. Fanger, commenting on the *ASHRAE Transactions* version of the paper, said that modern upholstered office furniture could add 0.1 to 0.2 clo to clothing insulation values of the study subjects.

Another reason why the field measurements may differ from the model predictions is activity level. Office workers might be more active than laboratory study subjects who are not actively working. Both Professor Fanger and Bjarne Olesen, of Virginia Polytechnic Institute, raised this point.

Activity Level Estimates

Bjarne Olesen has spent a great deal of his career studying thermal comfort as a researcher, on ASHRAE committees, and for his former employer, Bruel and Kjaer, who manufacture thermal environment measurement equipment. He wonders if the researchers had determined the subjects' activity levels during the half hour or hour prior to the measurements. Olesen said that their metabolic rates could have been higher than was apparent from their activities when the measurements were made. A small increase in metabolism, say from 1.2 met to 1.4 met, could make a significant difference in the results, he said.

K. M. Cena of Australia, who also studies thermal comfort, says "the main problem is accurate assessment of the subjects' activity." It is easy to see that a small change in activity would have a significant impact on PMV. In fact, Cena writes, elderly people he studied in a residential thermal comfort survey "thermoregulated by increasing their activity rather than by increasing their clothing insulation."

In *ASHRAE Transactions*, Fanger also said that we need more realistic activity levels; the levels used in the study [and for ASHRAE Standard 55 as well] are based on very old research. Fanger suggests that in more modern offices with stressful work the activity may very well be 1.3 met. However, Brager et al. calculated that if all other factors were held constant, it would require a met value of 1.75 for the results to match those of the models. Even though underestimates of clo and met values may have occurred, increasing them to 0.7 clo and 1.3 met is still not sufficient to explain all of the differences between the field study results and the models. Table 1 shows this.

The important point is that small changes in activity level can make fairly large differences in thermal comfort. This presents some real challenges to the designer as well as the building operator.

Expectations

Expectation and prior experience may have a substantial influence. Cena's work in Australia supports this hypothesis. He conducted a survey of Perth office workers in buildings without air-conditioning where fans were used regularly. Average summer afternoon temperature at 2 PM was about 27°C, with a maximum recorded during the study at 34°C. The average response was between slightly and moderately satisfied. Furthermore, no respondent ranked air temperature as the most important attribute for a satisfactory office environment.

Female office workers ranked air temperature below lighting, air quality, office furniture, and comfort of chairs. Below air temperature they ranked amount of space available, type and levels of sound, provision of non-smoking areas, and color of walls. On average, study subjects considered air conditioning to be only occasionally useful.

Cena reports that Humphrey's (1981) compiled results from thermal comfort surveys in a "free running" building (without heating or cooling installations) indicate that people accept the climatic conditions to which they are accustomed. Cena says that may imply that people become "...habituated to the environments they experience over a much wider range than is usually considered desirable in air-conditioned buildings."

Designing for Comfort

Since "you can't please all the people all the time," the challenge for architects, engineers, and building operators is to design and maintain buildings with thermal conditions that the fewest number of occupants will find uncomfortable. They have to determine the acceptable range of thermal conditions and then figure out how to maintain them. To determine an acceptable range, it is important to know how many occupants will be uncomfortable at any given temperature (and how many will be uncomfortable even at an optimal temperature). Complicating the designers' and operators' tasks are the most important factors that determine people's responses to the thermal environment: individual physiology, activity, and clothing. The designer or operator cannot control any of these factors.

Integrating Environmental Variables

Everyone knows the importance of radiant temperature — how good the sun feels even on a chilly day. We know that on a hot day, it can be quite comfortable in the shade even though it is uncomfortable in the direct sun. We also know how uncomfortable it can be to sit near a very cold window even when air temperatures are in the comfort range.

Air movement is important because it increases the evaporation rate of moisture from the skin. It also carries heat away from the body more rapidly. ASHRAE's thermal comfort standard allows for warmer temperatures if the air speed is increased above normal; for instance, increasing air velocity from 50 fpm (0.8 m/s) to 160 fpm (an impractical solution in offices) allows for maximum summer temperature increases from 79°F to 82.5°F (from 26°C to 28°C).

Humidity is also important because cooling by evaporation from the skin is decreased as humidity increases. Skin wettedness is an important determinant of thermal comfort sensation. We all have experienced being chilled when emerging from a shower, bath, or swimming, even though the air temperature was quite warm. This is because the evaporation of moisture occurs so rapidly when we are very wet that we experience very large heat loss and we perceive as coolness of the environment.

All these relationships illustrate the fundamental principal that thermal comfort is a function of heat exchange with the environment. Based on extensive research, these environmental factors are combined, using appropriate constants to weight their impacts in complicated mathematical expressions, to determine the effective temperature. This formula, not just the air temperature, is the actual basis for ASHRAE's thermal comfort standard. That is why the so-called thermal comfort "envelope" encompasses a range of air temperatures, humidities and air velocities.

Figure 1 showed the thermal comfort envelope as defined by ASHRAE Standard 55-1981. The revised version, 55-1991, is due out soon and does not significantly change the envelope shown in the figure.

Activity Level

Activity level and physiological make-up determine metabolic rate and strongly affect thermal comfort. ASHRAE has published a table of metabolic rates associated with various activities. The rate varies from a reclining person's 0.8 met units to 3.0 to 4.0 met units for a high activity rate (vigorous work or calisthenics/exercise). Office activities range from 1.0 met units for reading or writing to 1.7 met units for walking about and 2.1 met units for lifting or packing. Basketball and competitive wrestling are near the top of the list with met units of 5.0 to 8.7. A met unit equals the production of 18.43 Btu per hour per square foot of body area (Btu/h ft^2). The average adult male checks in with about 1.8 m^2 or 19 ft^2 of body area and would produce about 350 Btu/hour at an activity level of 1.0 met.

Sedentary activity levels typical of office workers are the basis of the thermal comfort standards. These rate at 1.2 met. The adult male office worker produces about 420 Btu/hr. This is roughly the waste heat produced by a 150-watt fluorescent lamp (80% waste heat, or about 120 watts of heat). A 130-watt incandescent lamp (95% waste heat) illustrates this well — we all know that a 120 watt light bulb gets quite hot - too hot to hold comfortably.

Clothing Levels

Besides activity, clothing is the other most important factor. If all that heat is generated and must be dissipated to maintain comfort (thermal neutrality), then the clothing ensemble must permit the loss of that heat and not much more. ASHRAE has adopted a table of clothing values for use in thermal comfort calculations. They give a sense of the relative insulation values of various clothing ensembles as determined by researchers using heated mannequins.

The values are provided in clo units which represent thermal resistance in °F • ft^2 • h/Btu. One clo equals 0.88°F • ft^2 • h/Btu. Table 2 shows some typical clo values (all including briefs or panties, socks, and shoes).

Although the importance of clothing is obvious, controlling it in building occupants is virtually impossible except in rare situations like the military, prisons, convents, and certain schools. Yet, clothing can have an enormous impact on the acceptability of the thermal en-

clo Value	Ensemble
0.5 clo	Fitted trousers and a short sleeve shirt.
0.54 clo	Knee length skirt, short-sleeve shirt, panty hose (no socks), and sandals.
0.96 clo	Fitted trousers, long sleeve shirt, and suit jacket.
0.77 clo	Sweat pants and a sweat shirt.
1.10 clo	Ankle length skirt, long-sleeve shirt, suit jacket, and panty hose (no socks).

Table 2 - Clo Values of Typical Clothing Ensembles.

vironment to building occupants, perhaps most importantly at non-ideal conditions. Assumptions about what people wear in winter and summer account for the two very different envelopes for the two seasons.

Application Is Difficult

So how can an architect, engineer, or building operator produce a building with the greatest occupant satisfaction and the fewest complaints?

In the past, we have relied on the laboratory studies of thermal comfort that try to identify the "optimal" temperature. These studies have been incorporated into design standards such as ASHRAE Standard 55-1981, "Thermal environmental conditions for human occupancy," and ISO Standard 7730, "Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions of thermal comfort." Building codes and other regulations incorporate these standards, and they are used by manufacturers to develop HVAC equipment and for designing environmental control systems for buildings.

The standards provide a range of values that we expect to satisfy 80% to 95% of building occupants. Generally they cover the range from about 68°F to 76 or 80°F (about 20°C to 26°C) within certain humidity limits, normal air movement, and minimal radiant asymmetry. Studies done at Yale University reinforce the University of California research suggesting that the existing standards may establish upper boundaries that are too high. At temperatures above 76°F, complaints about IAQ begin to rise significantly and satisfaction with thermal comfort declines rapidly. (See ***IAB*** Vol. 1, No. 7 and Vol. 2, No. 1 for some of these reports.)

ASHRAE now has projects that address some of the concerns raised in this article and in articles by Brager and her co-workers. One project is going to get data for other climates. A part of that project is now beginning in Australia. There may be others later. A second project will review the Fanger and Gagge models and survey the field data and see how they relate. Then the researchers will try to validate existing models with all available data. Finally, the researchers will identify issues for further research.

IAB Comments

Rohles, Woods, and Morey (1989) introduced the idea that it is necessary to know how individuals rate the importance of various environmental factors as well as how they rate their satisfaction with the certain conditions of each. Thus, while some study population may rate the thermal comfort low or unacceptable, if they also indicate that thermal comfort is very important, this is far more significant than if they indicate other factors more important.

Different studies have found that different factors were rated as more important than others. There is no broad consensus from either of the studies that have been reported or from the investigators doing them. Among the most important factors, Rohles' subjects rated thermal environment more important than acoustics, lighting, and air quality. Clerical workers also attached more importance to air temperature.

The challenge to researchers is to develop laboratory studies that will more closely predict what occurs in the field. Models are essential because not all field conditions can be adequately studied in a rigorous manner - at least not economically. At the same time, standards writers must be aware of the differences between the conditions under which research is conducted and the "real world" conditions the study results will be used to predict. Somehow, standards must reflect these differences if they are to be useful and reliable.

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Note: Gail Schiller is now Mrs. Gail Brager.

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