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A better way to predict comfort: the new ASHRAE standard 55-2004

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Abstract:
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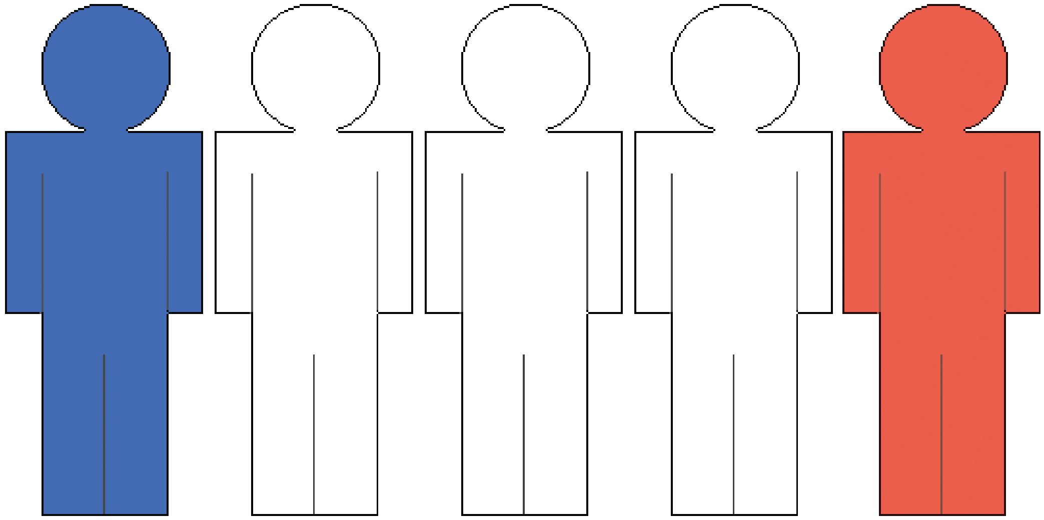
The standard specifies conditions of the indoor thermal environment that occupants will find acceptable. It is intended for use in design, commissioning, and testing of buildings and other occupied spaces and their HVAC systems, and for the evaluation of existing thermal environments. Because of the inherent variations in occupants' metabolic rates and clothing levels, and because it is not possible to prescribe or enforce what these should be, this standard cannot practically mandate operating setpoints for buildings.

The two most important additions included in this new standard are an analytical method based on the PMV-PPD indices and introduction of the concept of adaptation with a separate method for naturally conditioned buildings. The adaptive model and several other changes are based on various ASHRAE sponsored research projects. This article provides an overview of the key features and limits of applicability of Standard 55-2004.



A Better Way to Predict Comfort

By Bjarne W. Olesen, Ph.D., Fellow ASHRAE, and **Gail S. Brager, Ph.D.,** Fellow ASHRAE

Substantial progress in our understanding of human response to thermal environments has been made since Standard 55-1992, including the amendment 55-95a. Incorporating many of these advances, Standard 55-2004, *Thermal Environmental Conditions for Human Occupancy*, was recently published after completing four public reviews and receiving approval by both ASHRAE and the American National Standards Institute (ANSI).

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About the Authors

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The New ASHRAE Standard 55

Purpose and Scope of Standard 55

Standard 55 deals exclusively with thermal comfort in the indoor environment. The scope is not limited to any specific building type, so it may be used for residential or commercial buildings and for new or existing buildings. It also can apply to occupied spaces such as transportation means (e.g., cars, trains, planes and ships).

The standard specifies conditions acceptable to a majority of a group of occupants exposed to the same conditions within a space. The body of the standard clearly defines "majority" such that the requirements are based on 80% overall acceptability, while specific dissatisfaction limits vary for different sources of local discomfort. A space that meets the criteria of the standard likely will have individual occupants that are not satisfied due to large individual differences in preference and sensitivity.

The standard does not cover hot or cold stress in thermally extreme environments, or comfort in outdoor spaces. It also does not address non-thermal environmental conditions (e.g., air quality or acoustics), or the effect of any environmental factors on non-thermal human responses (e.g., the effect of humidity on health).

Predicting Thermal Comfort

Thermal comfort is essentially a subjective response, or state of mind, where a person expresses satisfaction with the thermal environment. While it may be partially influenced by a variety of contextual and cultural factors, a person's sense of thermal comfort is primarily a result of the body's heat exchange with the environment. This is influenced by four parameters that constitute the thermal environment (air temperature, radiant temperature, humidity and air speed), and two personal parameters (clothing and activity level, or metabolic rate). Methods for estimating clothing and metabolic rate are presented, respectively, in Appendix A and B of Standard 55-2004. New values for thermal insulation of chairs have been added in Appendix A.

With only limited exceptions, existing prediction tools for thermal comfort assume steady-state conditions. However, the standard does provide some requirements for non-steady state environments, although these requirements are based on limited laboratory data. While the methods are based on data derived primarily from studies with activity levels typical of office work (1 to 1.3 met [58.15 to 75.6 W/m^2]), some of the requirements may be applicable to moderately elevated activities.

People may be dissatisfied due to general (whole body) thermal comfort and/or due to local (partial body) thermal discomfort parameters (radiant asymmetry, draft, vertical air temperature difference, and floor surface temperature). Presently, no method exists for combining the percentages of dissatisfied people due to various factors to give an accurate prediction of the total number of people finding the environment unacceptable. For example, we don't know if the dissatisfaction resulting from general thermal discomfort is additive with the percentages of those who are dissatisfied due to local discomforts, or whether the total dissatisfied may be less than the sum of the individual percentages (i.e., some people complaining about more than one particular problem simultaneously).

To simplify the situation, Standard 55 has traditionally defined an acceptable thermal environment as one in which there is 80% overall acceptability, basing this on 10% dissatisfaction criteria for general thermal comfort, plus an additional 10% dissatisfaction that may occur on average from local thermal discomfort. The standard also specifies separate percent acceptability levels for the various physical variables that may cause local discomfort. These range from 5% to 20%.

The requirements for providing thermal comfort are all contained in Section 5 of Standard 55-2004. Section 5.2 represents the primary methodology for determining acceptable thermal conditions for most applications. It includes the PMV-PPD method for determining acceptable operative temperature for general thermal comfort (5.2.1), followed by additional requirements for humidity (5.2.2), air speed (5.2.3), local discomfort (5.2.4), and temperature variations with time (5.2.5). When Section 5.2 is used, all of the requirements of these subsections must be met. Section 5.3 presents a new alternative compliance method applicable for naturally conditioned buildings, based on an adaptive model of thermal comfort. Each of these sections gives specific requirements for thermal comfort, and defines the relevant limitations of applicability.

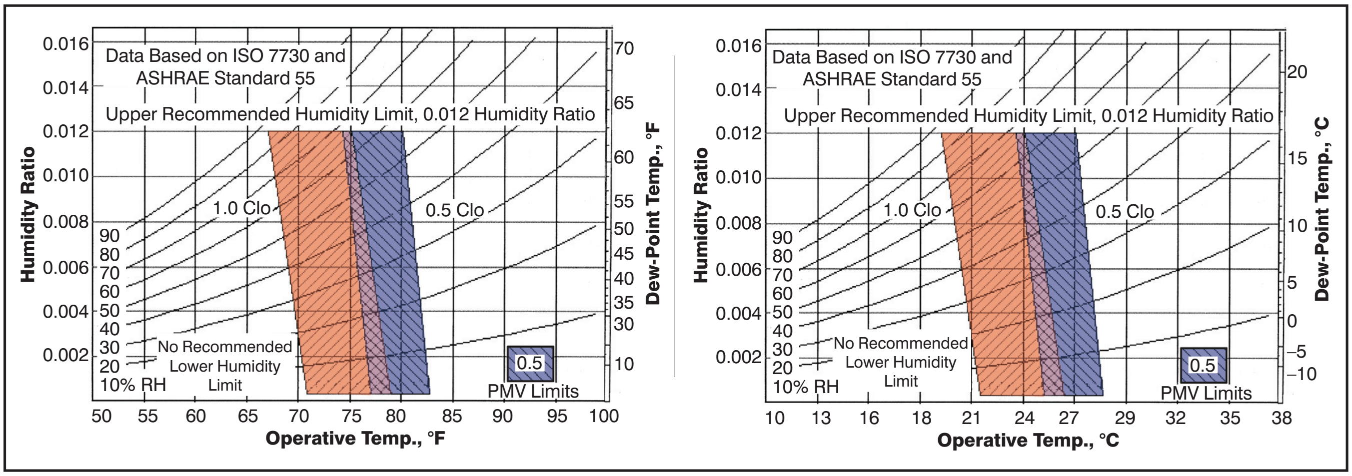

Figure 1: Acceptable range of operative temperature and humidity (for spaces that meet criteria specified in Section 5.2.1).

PMV/PPD Method

One of the most significant changes to Standard 55-92 was the inclusion of the PMV-PPD method of calculation to determine the comfort zone. Hopefully, this will result in engineers being more likely to use the calculation method to estimate the acceptable range of thermal conditions for their particular situation, rather than defaulting to the simpler graphic comfort zone, where the assumptions might not match their conditions. Standard 55 is now more consistent with other international standards, such as ISO EN 7730.[1]

PMV (Predicted Mean Vote) is an index that expresses the quality of the thermal environment as a mean value of the votes of a large group of persons on the ASHRAE seven-point thermal sensation scale (+3 hot, +2 warm, +1 slightly warm, 0 neutral, –1 slightly cool, –2 cool, –3 cold). PPD (Predicted Percentage Dissatisfied) is an index expressing the thermal comfort level as a percentage of thermally dissatisfied people, and is directly determined from PMV. The PPD index is based on the assumption that people voting ±2 or ±3 on the thermal sensation scale are dissatisfied, and the simplification that PPD is symmetric around a neutral PMV (=0). Both PMV and PPD are based on general (whole body) thermal comfort.

For specified values of the other four thermal comfort factors (humidity, air speed, clothing insulation and metabolic rate), a "comfort zone" can be defined in terms of a range of operative temperatures that result in a specified percentage of occupants who will find those conditions acceptable. Operative temperature is related to the dry heat exchange by both convection and radiation, and is often approximated by the simple average of the air temperature and mean radiant temperature (Appendix C of the standard provides more information about calculating operative temperature).

Section 5.2.1 offers both a simplified graphic method for determining the comfort zone for limited applications, and also a computer program that allows the user to run the PMV-PPD model for a wider range of applications. When using either method, one needs to assess or make assumptions about the occupants' metabolic rates and clothing insulation levels for the space being considered.

Graphical Method. Using the PMV-PPD model, the acceptable range of operative temperature is shown in a psychrometric chart for people wearing two different levels of clothing: 0.5 clo (0.08 $m^2 \cdot K/W$) (typical for summer or cooling season) and 1.0 clo (0.155 $m^2 \cdot K/W$) (typical for winter or heating season). The graphical comfort zones (*Figure 1*) correspond to a PPD of 10% (general thermal discomfort). The graphic zones are simple to use, but are only applicable for limited situations where metabolic rates are between 1.0 to 1.3 met (58.15 to 75.6 W/m^2), and air speed is less than 0.20 m/s (40 fpm). If clothing values are in-between 0.5 to 1.0 clo (0.08 to 0.155 $m^2 \cdot K/W$), one can determine the acceptable operative temperature range by linear interpolation between the limits found for each zone. While the separate comfort zones reflect the fact that people usually change clothing according to outside temperature or season, this is not always the case for workplaces that have a fixed dress code, or in geographical regions that have small seasonal variations, or where people might dress for an indoor climate that is consistent year-round (i.e., a constant setpoint temperature that doesn't change with the seasons).

It is important that people use this figure carefully, confirming that the selected clo levels associated with a comfort zone are appropriate for the building they are designing or evaluating.

Computer Method. The computer program for calculating the PMV and PPD indices is in Appendix D of Standard 55-2004. Although more complex than the graphical method, it can be applied to a wider range of conditions and allows the user to see the effects of altering the various factors affecting thermal comfort. The computer model itself is applicable for situations where clothing insulation is less than 1.5 clo (0.23 $m^2 \cdot K/W$), metabolic rates are between 1.0 to 2.0

met (58.15 to 75.6 W/m^2), and air speed up to 1 m/s (200 fpm). In Standard 55-2004 the use of the model is limited to air speeds less than 0.20 m/s (40 fpm). Higher air speeds can be used to increase the upper operative temperature limit in certain circumstances, as described in a later section. By inputting specific values of humidity, air speed, clothing, and metabolic rate, the model can be used to determine the operative temperature range that will produce a PMV within the range –0.5 < PMV < +0.5, which corresponds to a PPD of 10%. As described earlier, the 80% overall acceptability assumes 10% dissatisfaction for general thermal comfort (PPD), plus an additional 10% dissatisfaction that may simultaneously occur on average from local thermal discomfort.

Humidity

The scope of Standard 55 clearly states that its criteria are based only on thermal comfort. Therefore, Section 5.2.2 does not specify a minimum humidity level since no lower humidity limits relate exclusively to thermal comfort. The standard acknowledges, however, that there may be non-thermal factors that affect the acceptability of very low humidity environments, and designers should be aware of this even if it is beyond the scope of this standard.

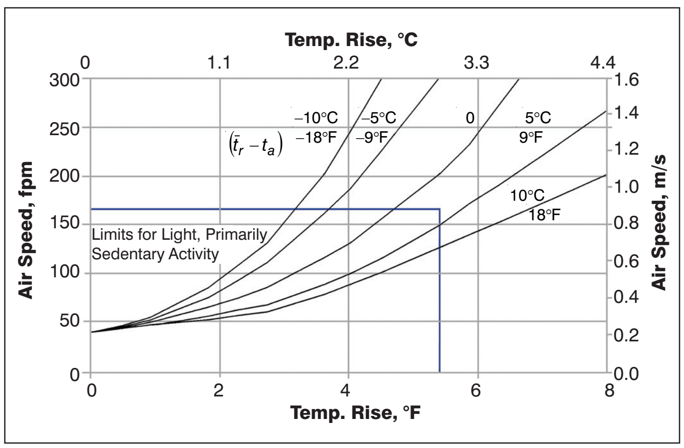

Figure 2: Air speed required to offset increased temperature from Section 5.2.3.

The form of the upper limit of humidity has changed throughout the standard's history. It was expressed in terms of a humidity ratio in 55-1981 (based originally on indoor air quality considerations), a relative humidity in 55-1992, and a wet-bulb temperature in 55-1995a. Regardless of which form was used in the past, the influence of humidity on preferred ambient temperature within the comfort range is relatively small. The committee decided to use the more simple absolute humidity as the limiting parameter and return to the upper limit used in 1981, namely a humidity ratio of 0.012. This upper humidity limit applies only to situations where there is a system in place designed to control humidity.

Air Speed

The operative temperature limits in Section 5.2.1 are based on a limit of air speed less than 0.20 m/s (40 fpm). However, higher levels of air movement can be beneficial for improving comfort at higher temperatures. Section 5.2.3 presents a graph (*Figure 2*) showing the relationship between elevated air speed and the temperature rise above the upper limit of the comfort zone (i.e., for a given air speed, what upper temperature limit would be acceptable; or for a given temperature rise, what air speed would be required). This figure is applicable for lightly clothed people with clothing insulation between 0.5 to 0.7 clo (0.08 to 0.1 m^2·K/W) and metabolic rates between 1.0 to 1.3 met (58.15 to 75.6 W/m^2), and in situations were occupants are individually able to control the air movement.

Limited data is available that shows the precise relationship between increased air speed and improved comfort, so the relationship is derived from theoretical calculations of equivalent heat loss from the skin, combined with professional judgment about reasonable limitations that should be placed on this allowance. Recent research sponsored by ASHRAE[2] has experimentally verified the diagram for occupants having individual control. This graph is especially important for commercial buildings that are primarily in cooling mode because of high internal loads, where there may be an opportunity to reduce energy use while improving comfort. This can be achieved by allowing the temperature to rise slightly towards the higher end of the comfort zone, while giving people the opportunity to individually control air movement through task/ambient conditioning systems, personal or ceiling fans, or operable windows.

Local Discomfort

The PMV and PPD indices express warm and cold discomfort for the body as a whole. However, thermal dissatisfaction also may be caused by unwanted cooling (or heating) of one particular part of the body (local discomfort). Local thermal discomfort may be caused by draft, high vertical temperature difference between head and ankles, too warm or too cool a floor, or by too high a radiant temperature asymmetry. The requirements for local thermal discomfort in Section 5.2.4 apply to lightly clothed people with clothing insulation between 0.5 to 0.7 clo (0.08 to 0.1 m^2·K/W), and metabolic rates between 1.0 to 1.3 met (58.15 to 75.6 W/m^2). The effect of local discomfort is greatest at lower activity or lighter clothing, so therefore, the risk of discomfort is lower for met > 1.3 (m^2·K/W > 0.1) and clo > 0.7 (W/m^2 > 75.6), and the requirements are conservative and also may be applied for these circumstances. While these requirements apply to the entire comfort zone, they are based on exposures where people are close to thermal neutrality (not cool, not warm). The allowable percent dissatisfied varies from 5% to 20%, based on the source of local

discomfort. Future studies will be required to develop information on the combined effect of general thermal comfort and local thermal comfort, or the combined effect of several local thermal discomfort parameters.

The forms of local discomfort discussed in Standard 55-2004 are:

Radiant Temperature Asymmetry. This refers to the non-uniform thermal radiation field around the body due to hot and cold surfaces and direct sunlight. Allowing for 5% dissatisfied, the standard provides separate physical limits for a warm or cool ceiling and a warm or cool wall to reflect the body's different sensitivities to these sources. For example, people are most sensitive to radiant asymmetry caused by warm ceilings or cool walls (such as windows).

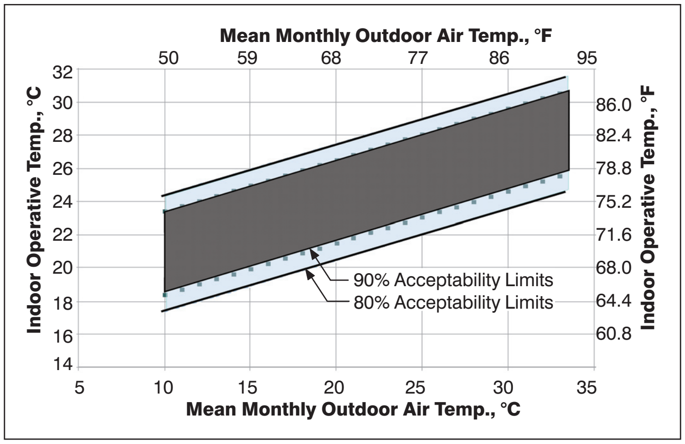

Figure 3: Acceptable operative temperature ranges for naturally conditioned spaces.

Draft. Air motion within a space may improve comfort under warm conditions, but also may produce a draft sensation in cooler conditions. Draft is defined as the unwanted local cooling of the body caused by air movement. The predicted percentage of people dissatisfied due to annoyance by draft is a function of local air temperature, air speed and turbulence intensity. The requirements in the standard for maximum allowable air speed are based on 20% dissatisfied. The model is based on the greatest sensitivity to draft — the head region with airflow from behind — and so the requirements may be conservative for other locations on the body and other directions of airflow. The criteria in this section do not apply to the use of elevated air speed under individual control for offsetting warm conditions, as presented in Section 5.2.3.

Vertical Air Temperature Difference. A large vertical air temperature difference between the head and ankles may cause

discomfort. Based on criteria of 5% dissatisfied, the allowable temperature difference is 3°C (5.4°F), which applies for situations where the temperature increases with height from the floor (i.e., the head is warmer than the feet). People are less sensitive to decreasing temperature, and no limits for this situation are included in the standard.

Floor Surface Temperature. If the floor is too warm or too cool, occupants may feel uncomfortable due to warm or cool feet. Based on criteria of 10% dissatisfied, the allowable range of floor surface temperature is 19°C to 29°C (66.2°F to 84.2°F), which is based on people wearing normal indoor shoes. The standard does not address situations where people are barefoot, or are sitting on the floor.

Temperature Variations With Time

Non-steady-state conditions in the form of fluctuations in air temperature and/or mean radiant temperature may affect occupants' thermal comfort. However, only limited research has been done on this subject.

The standard specifies limits on cyclic operative temperature variations (i.e., where the operative temperature repeatedly rises and falls within a period not greater than 15 minutes), expressed as an allowable peak-to-peak variation of 1.1°C (2.0°F). For cyclic variations with a period greater than 15 minutes, or for monotonic temperature drifts (passive temperature changes) and ramps (actively controlled temperature changes), the standard provides a table that specifies the maximum operative temperature change allowed within a given time period. The requirements of this section are applicable only for situations where the fluctuations are not under the direct control of the occupant.

Adaptation and Naturally Conditioned Buildings

Section 5.3 is a new optional method for determining acceptable thermal conditions in naturally conditioned spaces. It is applicable only for spaces where the thermal conditions are regulated primarily by the occupants through opening and closing of windows, there is no mechanical cooling (mechanical ventilation is allowed), and metabolic rates range from 1.0 to 1.3 met (58.15 to 75.6 W/m^2). The space may have a heating system in place, but this method does not apply when the heating system is in operation. The range of acceptable operative temperatures (*Figure 3*) is a function of outdoor temperature, and is based on an adaptive model of thermal comfort developed from an ASHRAE-sponsored research project.[3] The model is derived from a global database of 21,000 measurements taken primarily in office buildings from four different continents.

The research showed that, when occupants have control over operable windows and are accustomed to conditions that are more connected to the natural swings of the outdoor climate, the subjective notion of comfort and preferred temperatures change as a result of availability of control, different thermal experience, and resulting shifts in occupant perceptions or expectations. Since the model is based on field data that already accounts for people's clothing adaptation, it is not necessary to estimate the clo values for the space.

The field data also accounts for local thermal discomfort effects in typical buildings, so it is not necessary to address these factors when using this option. If the user believes that more extreme local conditions might occur, then they are encouraged to use the local thermal discomfort criteria in Section 5.2.4. No humidity limits are required (consistent with Section 5.2.2, which states that humidity limits are only applicable when there is a system designed to control humidity), and no air speed limits are required when this option is used.

Compliance

Section 6 states that building systems (combination of mechanical systems, control systems, and thermal envelopes)

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shall be designed so that, at design conditions, the thermal conditions of the spaces can be maintained within the specifications and also at all combinations of less extreme conditions (i.e., external climate and internal loads) that are expected to occur.

Engineers are used to the notion of design weather data, which represents certain percentages of exceedance of outdoor weather conditions (e.g., 1% design, four-month summer basis, 29 hours of exceedance), and recognize that it is impractical for HVAC systems to meet all loads encountered in its lifetime. Therefore, it is also expected that the thermal comfort requirements of this standard may not be met during excursions from those design conditions. Documentation requirements for comfort criteria have been expanded in Standard 55-2004, and include information such as tolerances, capacities and control of comfort variables, as well as building layout and maintenance.

Evaluation

In addition to being used for design, Standard 55 also can be used to evaluate existing thermal environments. For this purpose, Section 7 specifies the measurement positions, periods and conditions under which one should determine the effectiveness of the building at providing the environmental conditions specified in the standard. Validation of comfort (7.6) has been added to the evaluation section for 2004. There are two methods of evaluating compliance with comfort requirements. The first method involves an occupant survey (a sample is proved in Appendix E), and the second method analyzes environmental variables to determine comfort conditions.

Conclusion

Standing Standards Project Committee 55 is approved to operate under continuous maintenance and the committee has several goals for the next set of revisions. In real buildings, it may be desirable to establish different target levels of thermal dissatisfaction based on what is technically possible, what is economically viable, energy considerations, environmental pollution, or occupant performance. As such, it might be desirable for building professionals and clients to be able to make their own judgment about what percentage of the occupants should be satisfied in a given context for the environment to be deemed thermally acceptable.

Future changes to Standard 55-2004 likely will include an appendix that gives recommended levels of acceptance for three classes of environments (i.e., 6%, 10% and 15% dissatisfied), as is currently done in many international standards. There are also plans to develop new appendices elaborating on methods for compliance and evaluation, as well as develop more clear guidance for code-making bodies. SSPC 55 and TC 2.1 also are planning to cosponsor a user manual to accompany Standard 55-2004.

While the standard specifies conditions that will satisfy 80% of the occupants, that still may leave 20% dissatisfied. The best way to improve upon this level of acceptability is to provide occupants with personal control of their thermal environment, enabling them to compensate for inter- and intra-individual differences in preference. The market is seeing an increasing number of new workplace-based HVAC products that provide occupants with the ability to individually control airflow, air temperature and/or radiation.[4] To optimize the design and operation of such systems, a need exists for more research about the individual differences among occupants, as well as the combined effect of local asymmetries that may be more likely to occur in these environments. Ideally, such research would lead to future revisions of Standard 55 with the aim of providing comfort that reliably suits more than 80% of the occupants.

Acknowledgments

The authors gratefully acknowledge the many past and current members of SSPC 55 who contributed to ASHRAE Standard 55-2004. Although too numerous to mention here, they are listed on the inside cover of the standard. In particular, we would like to express our appreciation to the past and current Chairs of SSPC 55, Dan Int-Hout (1999–2001) and Wayne Dunn (2002–present), and to Stephen Turner who played a key role as master editor of the document.

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