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Advances to ASHRAE Standard 55 to encourage more effective building practice

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Advances to ASHRAE Standard 55 to encourage more effective building practice

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Abstract: ASHRAE Standard 55 has been evolving in recent years to encourage more sustainable building designs and operational practices. A series of changes address issues for which past design practice has been deficient or overly constrained. Some of the changes were enabled by findings from field studies of comfort and energy-efficiency, and others by new developments in the design- and building-management professions. The changes have been influencing practice and spurring follow-on research.

The Standard now addresses effects of elevated air movement, solar gain on the occupant, and draft at the ankles, each with several impacts on energy-efficient design and operation. It also addresses the most important source of discomfort in modern buildings, the large inter- and intra-personal variability in thermal comfort requirements, by classifying the occupants' personal control and adaptive options in a form that can be used in building rating systems. In order to facilitate design, new computer tools extend the use of the standard toward direct use in designers' workflow. The standard also includes provisions for monitoring and evaluating buildings in operation. This paper summarizes these developments and their underlying research, and attempts to look ahead.

Keywords: Standards, thermal comfort, building energy efficiency, design

1. Introduction

Since WW2, the miracle of air-conditioning has transformed the world and eased constraints on building designers. Sealed glass buildings with deep floor plates became common worldwide, many highly exposed to solar gain. Traditional window shading and cooling measures such as operable windows and ceiling fans went away. In commercial buildings, open-plan multi-occupant spaces became dominant in offices, classrooms, etc; mostly with central thermostatic control. In both cold- and warm-climate residential buildings, the norm became sealed envelopes in which AC and its temperature thermostat was the first recourse to comfort.

Indoor environmental standards reflected the engineering practice underlying this evolution –a focus on Ta, Tr, and RH, since they are the outputs of HVAC systems. Indices and models such as PMV/PPD established rational design practice. The ideal indoor climate was 'Cool, dry, and still'. 'Climatic design' based on outdoor-indoor interactions went out of fashion, (persisting a bit longer in the UK and its ex-colonies, and in the residential sector).

Like a genie released from a bottle, the miracle had significant downsides. The new AC-based building designs demanded a lot of energy. After originating and taking over in energy-rich developed-countries, the air-conditioned methods and 'international' building styles spread rapidly in the developing world, creating a potentially gigantic energy demand.

There was an energy shock in the 70's, stirring up a reaction that attempted to revive traditional climate-responsive design methods, but it gained little traction with the mainstream. The principal achievements were in energy simulation models, and standards for tighter envelopes and more efficient equipment. Michael Humphreys and Fergus Nichol were making fundamental contributions addressing the adaptive behavior of occupants, but at the time these were not taken up in practice or in indoor environmental standards.

An important milestone in the early 80's was Larry Berglund's and Fred Rohles' idea for an ASHRAE project to measure the success of its comfort standards in the field. This grew into a series of well-instrumented studies (RPs 462, 702, 821, 921) that generated significant amounts of detailed data on comfort and associated environmental conditions. ASHRAE then funded a project to examine adaptation (RP 884) which was carried out by deDear and Brager (deDear and Brager, 1998). This project assembled a database of the previous field studies, allowing them to quantify that there was a difference between comfort responses from air-conditioned (AC) and naturally ventilated (NV) buildings with operable windows, and to create an adaptive model that Standard 55 adopted in 2004.

The adaptive model was highly restricted in the standard (applicable only in non-cooled spaces) but it raised a surprising level of interest internationally, particularly among architects, for whom it broadened their design options beyond that of the sealed box. It permitted another look at NV design with operable windows, and mixed-mode designs. The causes for the observed adaptive differences were largely hypothetical, but many people began looking into it.

During this time, it became clear that there were major energy savings from allowing the interior setpoint range to widen. Every 1C extension at indoor air temperature setpoint toward the warm side saves 5 to 10% of a building's total HVAC energy, depending on the HVAC systems involved. These numbers have been found in both simulations and field studies, commercial and residential buildings, temperate (Hoyt et al. 2014) and tropical climates (Sekhar 1995, Rim et al 2015, Duarte et al. 2019).

It made sense to consider the energy implications of designs and operating approaches that were regulated by the standard, and to critically review barriers that the standard was imposing on promising practice.

In the following, we present some of the changes to the standard made since the adaptive model. We also present significant research underlying the standard changes, and tools to enable their use in practice. They are presented in no particular order:

- Elevated indoor air movement in building design and operation—2009, 2015.

- Model of solar gain on occupants for use in design of fenestration and solar control—2016.
- Thermal control classification for rating personal comfort systems and accommodating individual occupants' variable thermal requirements, for design, certification, and operation—2020.
- Smaller items: seasonal clothing insulation model—2013, thermal stratification limit—2014, draft at ankles—2017.
- New supporting research data: A) expanded comfort database--2018, B) clothing database--2018, 2020, C) research on the comfort and energy effects of reducing VAV minimum flowrates.
- New official thermal-comfort computer tool for designers—2017.
- Methods for measuring and evaluating comfort in operating buildings; plus best-practice guides—2010-2013.
- Providing comfort in transient spaces—in process.

These 12 developments are handled in different ways in the standard. They raise some interesting issues about the various roles of standards in encouraging best practice design and operation.

2. Air movement considerations

The most efficient solutions to adaptive comfort in neutral-to-warm environments involve cooling the occupant with air movement. In earlier standards its use was restricted to temperatures above 26C, and individual occupant control was mandatory. For most HVAC design situations, the draft risk model was the only design consideration. Fountain (1991) was the first to attempt to explicitly balance the positive cooling contributions of air movement with the negative draft concerns.

In 2004 and 2007 respectively Toftum and Arens et al. used the ASHRAE RP 884 comfort database to learn that occupants preferred higher levels of air movement than expected, even down into the 'slightly cool' sensation zone, and that this phenomenon applied in both AC and NV buildings. This led to a reexamination of how air movement was being dealt with in the standard, and how to encourage it as an integral part of environmental control throughout the seasons of year. A new approach was first adopted in the 2010 standard.

The sensible and evaporative cooling effect of air movement are now evaluated using the Standard Effective Temperature model (SET) (Gagge and Fobelets 1986). This generates the equal-comfort curves in Figure 1, which are applied over the full width of any given comfort zone. The figure contains an important feature—subzones based on access to air speed control. They are based on an empirical temperature dependence observed in Comfort Database 1, in which imposed air movement was seen to become acceptable above 22.5C. The Standard imposes a maximum (0.8m/s) for imposed air speed, but no maximum for group control. It also has simplified the previous draft risk provisions. The new air-movement approach applies to both air-conditioned and naturally-ventilated building types, and is integrated into the CBE/ASHRAE Thermal Comfort Tool described later.

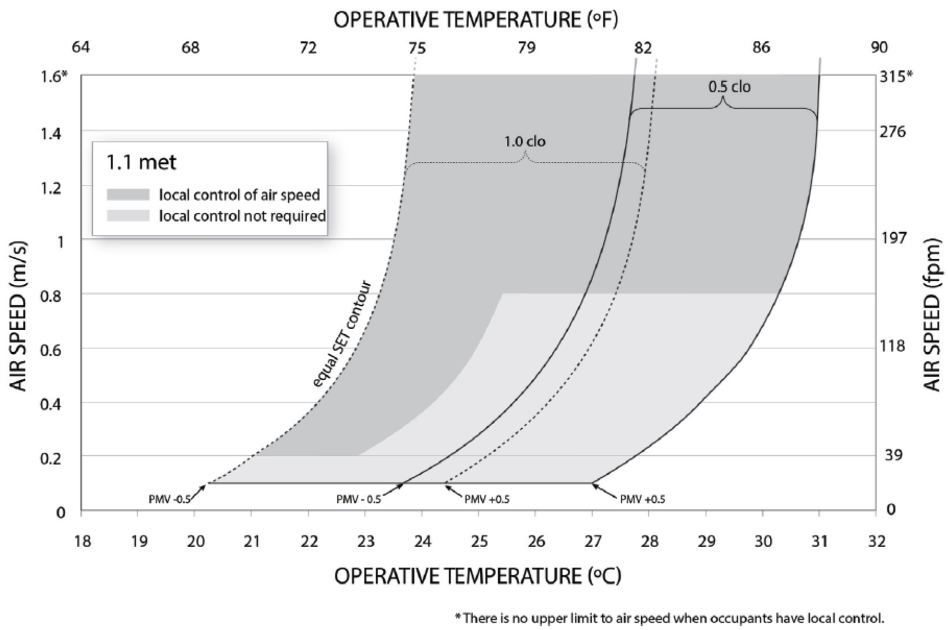


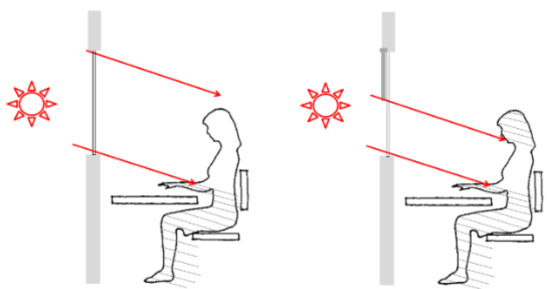
Figure 1. Acceptable ranges of operative temperature t_o and average air speed V_a for the 1.0 and 0.5 clo comfort zones, at humidity ratio 0.010

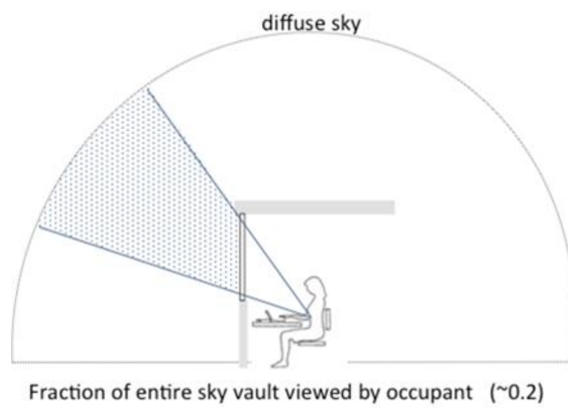
The new air speed provisions have attracted a great deal of interest, with much new research underway on how to create effective air movement within rooms. Huang et al. 2014, Gao et al. 2017, Zhai et al. 2017, Lipcynska 2018, are just a selection of papers examining design issues related to room fans. The integration of fan speed control with HVAC temperature setpoints is only just beginning, but products are now in the market.

3. Solar control.

Solar radiation on working occupants indoors almost always results in discomfort. In addition, most low-energy design strategies cannot succeed in inappropriately shaded buildings. In spite of their comfort and energy drawbacks, highly glazed unshaded buildings have become the norm. Up until 2017, indoor solar radiation was not addressed in any thermal comfort standard. It was as if engineers had no role at all in dealing with the problem. An addendum containing new performance- and prescriptive compliance approaches was added to Standard 55 in 2017 (Arens et al 2018). Direct- and diffuse shortwave gains on occupants are now evaluated in order to predict the amount of HVAC cooling required to offset them, and to prod both architects and engineers to become more engaged in shading design. The prediction is done using the ‘SolarCal’ model (Arens et al 2015), which is also incorporated in the CBE/ASHRAE Thermal Comfort Tool.

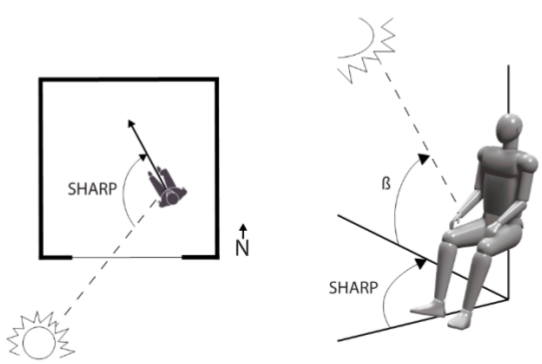
The model is simplified to require only inputs that designers can realistically provide at an early design stage. It uses minimal geometrical definition of interior architecture and workstation furnishings, defining them in terms of occupant-centric variables new to the standard. These are: the posture and orientation of the representative occupant relative to the sun, and the extent of the person’s body area exposed to direct sun and the diffuse sky vault. The shortwave gain is added into the standard’s PMV prediction as additional mean radiant temperature.





a) Fraction of body exposed to sun (not including the body’s self-shading)

b) Fraction of entire sky vault viewed by occupant (~0.2 in this example)



c) Solar horizontal angle relative to the front of the person (SHARP) and solar altitude *β*

Figure 2. Occupant-centric components of the solar model

Recently software developers have modified the SolarCal model to read in output from Radiance and EnergyPlus, allowing the model to predict annual solar comfort effects and facilitating its adoption within current architectural workflow (Zani et al. 2018).

4. Thermal Environmental Control Classification

Addendum C to the 2017 Standard assigns credit to the degree of individual comfort control available to the occupants (adopted February 2020). Based on evidence that achieving high rates of thermal satisfaction requires individual control (Karmann et al. 2018), a five-level 'thermal environmental control' classification scheme now rates the degree of control available to occupants. The degree of control is quantified by the number of options made available by the building and its management to individual occupants. Options include personal comfort systems, group control of ceiling fans and thermostats, etc. Their eligibility in the Standard is determined by their comfort-correcting power as measured in degrees temperature (Zhang et al. 2015a). .

The definition of 'corrective power' in the standard is: 'the ability of a PCS system expressed in degrees (°C, °F) to "correct" thermal conditions toward the comfort zone, measured as the difference between two operative temperatures at which equal thermal sensation is achieved - one a temperature in the comfort zone with no PCS, and one with PCS in use, with all other environmental factors held constant.'

The new classification approach is aimed at building rating systems, such as LEED and WELL, and by real-estate managers. Each of these are now rating the quality of office environments in operation as well as design. Basing an environmental control classification on the availability of occupant control options is a promising new approach in comfort standards, encouraging designs and practice that have lower dissatisfaction percentages and higher energy-efficiency. The classification is summarized in Tables 1 and 2; the first describing the numbers of control measures per classification level, and the second the criteria for accepting PCS devices as control measures. There are numerous papers describing the performance of the compliant types of PCS devices, (Luo et al. 2018, Zhang et al. 2015b, Pasut et al. 2015, Kim et al. 2019), in addition to fans as described previously.

Table 1: Thermal Environmental Control Classification Levels (from Std 55-2017).

Comfort Control Classification Level	Control Measure(s) for Environmental Factors Required to Achieve Level	Informative Examples Meeting Comfort Control Classification Levels
1	Each occupant is provided two or more control measures for their personal environment	• Private office with a ceiling fan and an occupant-adjustable thermostat • Shared office with a desktop fan and foot warmer for each occupant
2	Each occupant is provided one control measure for their personal environment	• Private office with an occupant-adjustable thermostat • Shared office with a desktop fan for each occupant

3	The room or *thermal zone* provides multi-occupant control of at least two control measures in their shared environment.	• Shared office with an occupant adjustable thermostat and ceiling fan control
4	The room or *thermal zone* provides multi-occupant control of one control measure in their shared environment.	• Shared office with an occupant adjustable thermostat
5	No occupant control of any environmental factors	• Shared or private office with an unadjustable thermostat or no thermostat

Table 2: Prescriptively Compliant Personal Comfort Systems (from Std 55-2017)

Description	Requirements
Cooling	
Desk fan aimed at head/face/upper body	Capable of providing air speed at the occupant's head/face/upper body within range of 0.36 – 0.8 m/s (70.9 – 157.5 fpm)
Cooled chair	Capable of extracting 20 watts from the body
Heating	
Footwarmer	Capable of adding 6 W to the body
Heated chair	Capable of adding 14 W to the body

This new classification is a different approach from the ISO PMV-based classification system in which narrow temperature deadbands are rated as providing superior environments (ISO 2005, CEN 2007). Conforming to the higher classification levels in these systems is highly energy-intensive. Of equal concern, examination of the two ASHRAE comfort databases and individual field studies show that the higher classification levels do not actually improve occupant comfort (Li et al., 2019, Lipczynska et al., 2018). Narrow room temperature control basically cannot solve the wide interpersonal variation in occupants' thermal comfort requirements. In addition, research consistently points to deficiencies in the predictive value of PMV and PPD, the measures underlying the ISO classification system.

5. Smaller elements

5.1. **A clothing insulation model** was added in 2015 to give designers a standard way of incorporating seasonal clothing behavioral changes in their designs. Clothing insulation on a given day is based on outdoor air temperature at 6 AM (Figure 3). The model is based on analyses of the ASHRAE databased of thermal comfort field studies (Schiavon and Lee, 2013, 2014).

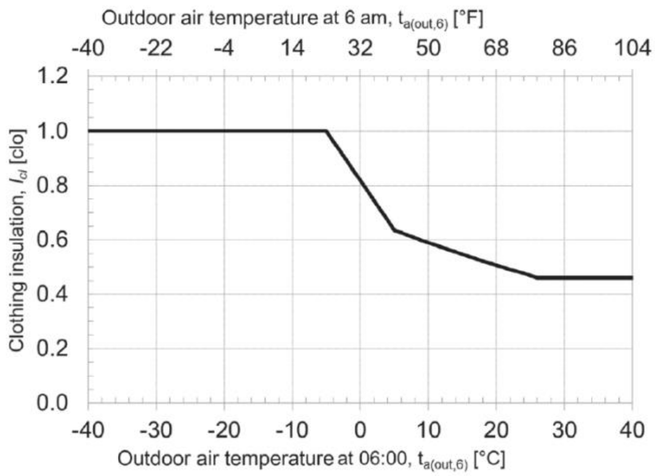


Figure 3. Clothing insulation as a function of outdoor air temperature

5.2. **The vertical thermal stratification** limit was in 2014 clarified to be 4K for standing and 3K for seated occupants. The original limit of 3 K between head and ankle had been applied in another standard to standing occupants, resulting in a 2K effective limit when seated. This was found to be adversely impacting the design and operation of displacement ventilation (DV) and underfloor air distribution (UFAD) systems (Bauman et al 2010).

5.3. **Ankle draft risk model**, approved and published as Addendum A in 2017. Draft, or unwanted local cooling caused by air movement, is a major issue for both DV and UFAD system manufacturers and designers (Melikov et al., 2005). Occupied floor area, mechanical system sizing, and energy use depend are all impacted. Since the exposure is at feet and ankles, the traditional Draft Risk model (Fanger et al., 1988) based on upper body dorsal exposure did not apply. A new model predicts percentage dissatisfied with ankle draft as a function of whole body thermal sensation and air speed at the ankles (Figure 4), (Liu et al., 2016, Schiavon et al., 2016).

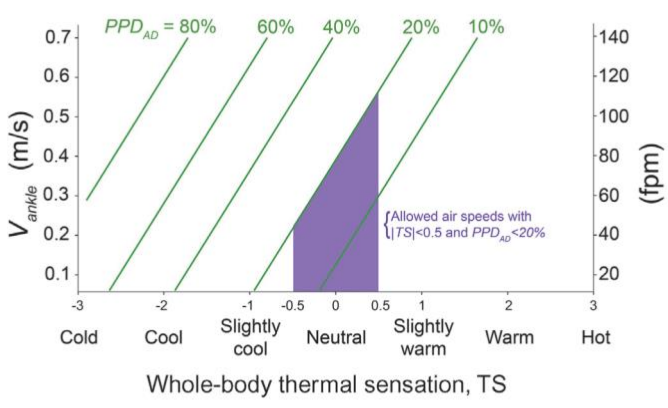


Figure 4: Air speed limits at 0.1 m (4 in.) above the floor as a function of whole-body thermal sensation and the predicted percentage of dissatisfied with ankle draft (PPD_{AD})

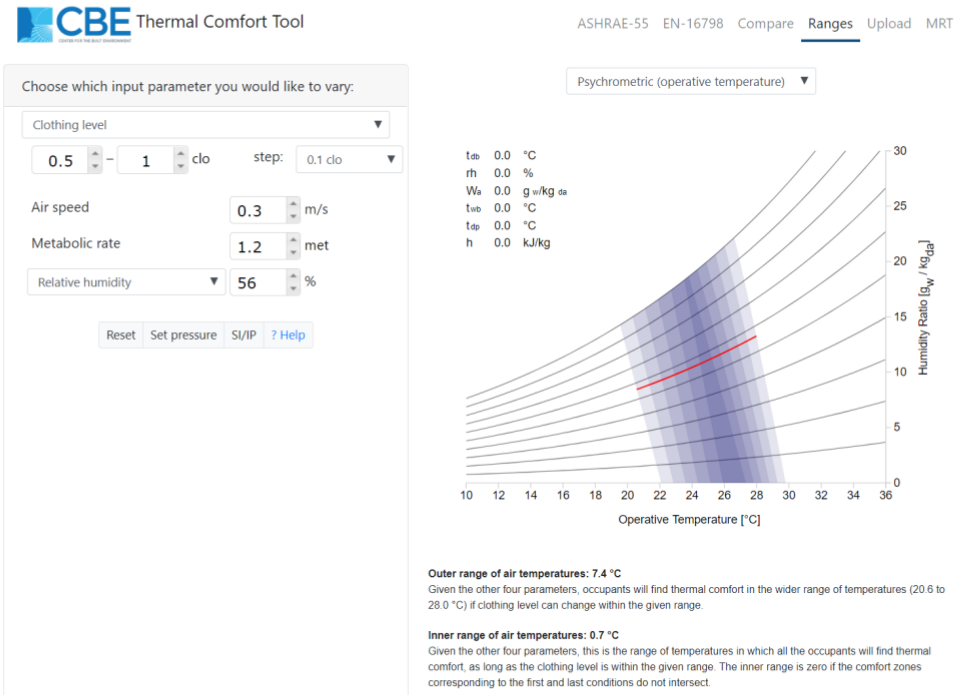
In the model, the whole-body thermal sensation is approximated using PMV with the input air temperature and speed averaged over two heights, and not three as in the rest of the standard. The two heights are 0.6 m and 1.1 m for seated occupants and 1.1 m and 1.7 m for standing occupants.

This type of draft risk might also occur in perimeter zones in which there are large glazed areas that are relatively cool. An architecture firm has developed an open web tool that incorporates this ankle draft risk model. https://www.payette.com/glazing-and-winter-comfort-tool/

6. ASHRAE/CBE Thermal Comfort Tool

The CBE Thermal Comfort Tool is a free web-based application that allows building designers and other practitioners to perform thermal comfort calculations (Schiavon et al. 2014, Hoyt et al. 2019). It complies with the ASHRAE Standard 55 and the European Standards EN-15251. It was launched in 2017 as the official tool for ASHRAE, with upgrades in 2019. The tool has been used by over 48,000 unique users, with 94,000 sessions per year from users around the world. At this point, the largest number of users are from the US (25% of total), Brazil, and the UK. https://comfort.cbe.berkeley.edu/ .

a)



b)

Figure 5: a) main screen, b) comparison screen showing comfort zones for a range of clothing

The tool incorporates the: PMV model for determining a representative occupant's thermal sensation in still air, the SET model for determining the cooling effect of air movement, the adaptive model for non-air conditioned buildings, the SolarCal model for solar gain on people, the dynamic predictive clothing model, and several local discomfort models (radiant temperature asymmetry, draft, ankle draft, vertical air temperature difference, and floor surface temperature).

The CBE thermal comfort tool serves many uses. One can compare various design scenarios, assess the effect of the variation of one of the variables (for example air speed) on the thermal comfort range, calculate the major thermal comfort indices for a large set of measured or simulated data; and accurately model the mean radiant temperature in a room.

The Thermal Comfort Tool has been integrated with EnergyPlus and Radiance to obtain more detailed input values needed for time-series calculations, and to integrate it into modern design workflow (Zani et al., 2018).

7. Standard-55-oriented research data

7.1. ASHRAE Global Thermal Comfort Database II

The original Global Thermal Comfort Database created in 1998 served to develop the Standard 55 adaptive model, the elevated air movement model, and the climate-based clothing model.

It was also extensively used to study analytic and adaptation models across climatic zones and cultures. Since many additional field studies have been completed since 1998, funding was secured from ASHRAE in 2015 to support the collection and consolidation of all available datasets. Completed in 2019, the ASHRAE Global Thermal Comfort Database II contains data from 43 research projects, all voluntarily donated (Foldvary et al, 2019). The database is 6x larger, and the number of represented countries increased to 23. The dataset is accompanied by software tools for visually exploring and analyzing the data. A large number of analytical studies have been done with the data within the first year since the publication of the data.

One of these (Parkinson et al 2020) evaluated the adaptive model and found that people in all types of buildings (AC, MM, NV) adapt to the *indoor* thermal environment. This is a breakthrough because it suggests, among other things, that adaptive models can be applied to any type of building. Other studies have used the new database to examine the effectiveness of existing comfort indices (Cheung et al, 2019).

The new database is openly accessible at: http://www.comfortdatabase.com/ (Parkinson 2018). The interactive visualization tool (Pigman 2014, Cheung and Pigman 2018) is accessible at https://cbe-berkeley.shinyapps.io/comfortdatabase/ .

7.2. **ASHRAE databases of Non-Western and Western clothing**

The absence of non-western clothing ensembles had been a long-standing concern in the Standard 55 committee, so ASHRAE TC 2.1 sponsored a major international study of worldwide non-western clothing insulation, performed by a team led by Loughborough University (RP 1504) (Havenith et al. 2016). New standardized measurement procedures were developed to coordinate the several universities that participated in the project. Clothing insulation was quantified at the body segment level, to support advanced comfort models in the future. Vapor permeability was determined as well. When this project was completed in 2016, it was clear that the existing western clothing data in the Standard would have to raised to the same level, and that it needed to accommodate additional modern clothing trends. A second ASHRAE research project, RP 1760, is currently underway at Loughborough to fulfil that objective.

7.3. **Comfort and energy effects of reducing minimum airflow rates from variable-air-volume (VAV) diffusers**

ASHRAE Research Project 1515 was co-sponsored by the Standard 55 committee. It examined the impact of diffusers dumping cooled air on occupants as VAV systems throttle back under reduced loads. It found that the traditional design concern about drafts from dumping is unsupported, but also that the high minimum flow setpoints used by the industry to avoid dumping are the most probable cause of the widespread overcooling of buildings in summer (Paliaga, 2019). This is an example of research addressing the intersection of comfort and energy standards. It describes a cold comfort problem that does not occur during typical winter design-day conditions, but occurs instead during frequent periods of low occupancy in the warm season. To date, some state building energy standards have been modified to take advantage of its findings.

8. Evaluating comfort in operating buildings.

Standard 55 also addresses the evaluation of buildings in operation. The provisions are contained in normative and informative sections in the standard's Section 7 and Informative Appendix L. They were developed around 2011 and incorporated in the 2013 Standard, and include:

- Evaluation approaches based on 1) physical environmental measurements and models, and 2) occupant surveys, giving criteria and examples for each. There is increasing use in the industry of physical monitoring over time, and of web-based survey tools (Heinzerling 2013, Parkinson 2019).
- Exceedance metrics for comfort and acceptability as measured over time. These include the definition of exceedance-hours specified in the normative standard itself, and the definition of other measures (weighting by severity of temperature exceedance, thermal sensation exceedance, rate-of-change exceedance, and numbers of discomfort episodes) specified in the standard's informative appendices. Since 2011 there has been considerable work done on exceedance assessment in operating buildings (Borgeson and Brager, 2011, Carlucci 2013).

Table 3 gives the structure of the section's provisions. They include both physical and subjective metrics for evaluating spaces, each divided into short-term (spot) measurements, and long-term satisfaction and exceedance measurement. The intended uses of the metrics are provided as informative notes.

TABLE 3 Comfort Evaluation Approaches for Various Applications (source: ASHRAE Standard 55-2017)

		Nature of Application	
Measurement Method		**Short-Term**	**Long-Term**
	Occupant Surveys	**Right-Now/Point-in-Time Survey (must survey relevant times and population):** • Binning (TSENS scores) leads to % comfort exceedance during period of survey. • Needs coincident temperature to extrapolate to full range of conditions *(Used for research, problem diagnostics)*	**Occupant Satisfaction Survey:** • Survey scores give % dissatisfied directly. ('dissatisfaction' may be interpreted to start either below -1, or below 0) • Time period of interest can be specified to survey takers.

			(Used for building management, commissioning, rating operators and real estate value, compliance with green building rating systems)
	Environmental Measurements	**Spot Measurements, Temporary (Mobile) Sensors (must select a relevant time to measure):** • Use measurements to determine PMV (Sections 5.3.1, 5.3.3) • Use measurements to determine compliance with *adaptive model* (Section 5.4). *(Used for real-time operation, testing and validating system performance)*	**Logging Sensors over Period of Interest, or Trend Data from Permanently Installed (BAS) Sensors:** • *Exceedance hours*: sum of hours over PMV or Adaptive Model limits. • Binned exceedances may be weighted by their severity. • Instances of excessive rate-of-temperature change or of local thermal discomfort can be counted *(Used for evaluating system and operator performance over time)*

The primary users are facilities management and certification programs that evaluate and rate building performance over time. Such programs should ideally involve the same level of rigor as required in design standards.

To support such users, ASHRAE prepared Performance Measurement Protocols [ASHRAE 2012] for measuring indoor environmental quality, a best-practices guide presenting examples of the methods contained in Standard 55.

9. Looking forward: dealing with thermal comfort transitions

SSPC55 is currently discussing standards for designing and operating spaces in which comfort transients occur. Such spaces are ubiquitous and economically/environmentally important. Designing for them will ultimately require a dynamic model of comfort, enabling a kind of choreographic design for comfort sequences. For now, prescriptive measures may suffice. The new provisions would be applicable to:

1) transition zones (lobbies, stores, transit facilities)
2) interior sedentary destination zones (offices, classrooms, restaurants,)

Building *lobbies*, *retail stores*, and *transit* facilities must maintain comfort for people moving between outdoor and indoor environments. Their users' immediate and short-term comfort perceptions impact the use of such spaces, affecting their profitability. At a broader scale, transient comfort directly affects the success of public transit and non-automotive commute strategies intended to improve transportation energy-efficiency.

Transient comfort also affects the environmental control of indoor spaces in which people are primarily sedentary, such as *offices*, *restaurants*, *airport lounges*, because when people arrive in these places they must undergo a transition from a moving- to sedentary state. This must occur as rapidly as possible so the occupants do not overheat and register discomfort to the building

HVAC controller. During the transition period, arrivees' thermal requirements may differ from those of surrounding occupants, and their efforts to change the thermostat may overcool the other occupants. Even if there are no other occupants, the response time lag in HVAC systems is often too long for effective at comfort restoration, and the reduced temperatures persist when they are no longer needed.

For both of the above types of comfort control, there are significant energy implications. In transitional spaces such as lobbies and stores, either heated or cooled conditioned air leaks to the outdoors, so its temperature matters. In destination sedentary locations such as offices, rooms are being operated cooler-than-comfortable for long-term occupants, to accommodate the cooling-off of arriving occupants.

For these transient cool-downs, it turns out that air movement is the most rapid and comfortable cooling mechanism (Zhai et al., 2019a, b). Fan air movement around the occupant is also inherently many times more energy-efficient than cooling the indoor air or surfaces. Store/lobby temperatures can therefore be higher and their leaked air does not carry as much heat. Air cooling can be focused on the arriving occupant while sparing the already sedentary occupants from experiencing an overcooled space. In addition, fans often offer more opportunities for individual adjustment than thermostats. The question for the Standards Committee going forward is, how may one encourage such more effective design approaches within the terms of a standard?

10. Conclusion

This paper has

1) described what has been happening recently in ASHRAE Standard 55, and hopefully

2) raised questions about how comfort standards might perform roles that go beyond insuring that buildings and mechanical system meet predicted extreme conditions, and instead encourage generally better design and operation. These roles include: rewarding building designs and systems that are efficient over time, realistically rating buildings' comfort quality levels, dealing with predictable thermal transients in spaces and occupancies, and monitoring and control of existing spaces using greater input from sensors and occupants.

Standard 55 is generally considered to be a design standard but its title and scope do not actually state this. The definitions in its *Section 4* discuss the 'representative occupant' but do not exclude simulating larger numbers of occupants, or actually measuring their comfort to appraise and control existing buildings. There is scope for more roles for the Standard.

Standard 55's *Section 5* is entitled: 'Conditions That Provide Thermal Comfort'. The recent addenda described in this paper related to modeling air movement, solar effects on occupants, ankle draft, and clothing, have each been added into Section 5, which at present addresses only physical environmental conditions. Psychological and physiological adaptive opportunities are not explicitly part of the section, though one could say they are indirectly embodied within the comfort ranges provided by the empirical adaptive model. The physical conditions discussed in Section 5 are steady-state, with some limits to allowable rates of change. The Section does not deal with variation in the occupant's experience while moving through space or changing activity level (e.g. walking in and sitting down), even though these are often significant parts of the indoor experience in buildings. Also, the current prevalence of summer overcooling is affecting the occupants' adaptation to the environment—how should the standard encourage an appropriate comfort zone for the season?

Section 6 is entitled 'Design Compliance'. Recent research allows us to quantify the effectiveness of some individual adaptive opportunities (such as personal comfort systems), but devices like these are currently not considered part of the building's design or installed equipment. So they are included in in Section 6 compliance documentation as a comfort classification system. Their audience is third-party green-building rating systems. Under what circumstances could they become incorporated in design and dealt with as part of Section 5 of the standard? There are both technical and design-related issues to solve. The ceiling fan, attached to the building, is an intermediate step that should ultimately become integrated with HVAC design for more efficient and individually-responsive environments. In the future, it may be that the encouragement of efficient transient-comfort control has to begin as a quality-rating scheme within Section 6 design compliance documentation. The operable window, providing a mix of physical and psychological effects, might similarly be rewarded in a comfort classification scheme.

Section 7 is 'Evaluation of Comfort in Existing Buildings'. The building professions have not used this section much in the past. Where they have, it has been primarily for initial commissioning, problem diagnosis, and in using the exceedence metrics in yearly simulations of predicted comfort. There is however growth and interest in 'continuous (re)commissioning', more ubiquitous sensing, obtaining occupant feedback via computer surveys and control apps, and in determining individuals' and groups comfort profiles via machine learning. Such procedures could be used for both control and comfort classification. Section 7 may perform additional roles in the future.

11. Acknowledgment:

The authors prepared this paper as a contribution to IEA Annex 69, *"Strategy and practice of adaptive thermal comfort in low energy buildings"*. Most of the described additions to Standard 55 address adaptive attributes of thermal comfort, in order to put them to use in designing and operating more comfortable and energy-efficient buildings.

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