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FIGURE 1 Comfort vs. view: Office worker at perimeter workstation chooses a spot in direct sun with mostly raised shade for viewing San Francisco skyline. PHOTO CREDIT: CHRISTOPHER HUGHES

Updates to Standard 55

Sunlight and Indoor Thermal Comfort

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ASHRAE Standard 55-2017 has adopted new provisions to ensure thermal comfort for occupants exposed to solar radiation indoors.[1] Normative Appendix C provides the analytical method, and both prescriptive and performance-based approaches to compliance are incorporated within Section 5.3 of the standard.

Direct solar (aka shortwave) radiation entering buildings through windows (*Figure 1,* above) often introduces significant problems. Some of the problems are visual, such as glare, but three thermal ones are also important.

First, in most buildings the heat gain from solar radiation absorbed indoors must be removed by energy-intensive air conditioning.

Second, solar gain in the occupied zone is intensely variable and difficult to control: in attempting to keep the temperature of a sunlit section under control, adjacent spaces are likely to be overcooled.

A third issue is the topic here: solar radiation landing on occupants directly affects their thermal comfort.

The solar heat absorbed and liberated in clothing and skin must be offset by cooler air and surface temperatures around the body for the occupant to remain comfortably in thermal balance. The temperature offset to maintain comfort may be substantial, likely beyond the corrective capacity of conventional cooling systems, and difficult to achieve when all occupants are not equally exposed to sun.

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This issue has received surprisingly little notice in the design or evaluation of buildings. For example, Standard 55 has in the past not even mentioned shortwave radiation. This is true also for the ISO and European environmental standards.[2,3] Although Fanger published projected area factors for the human body in 1970,[4] the subject of shortwave gain and comfort has been almost absent from the research literature until recently. Very few studies[5–9] have addressed the effects of solar heating on comfort.

There also are no readily available design tools for predicting the comfort effect of solar radiation falling directly on occupants in buildings. Potential developers of such tools may have been discouraged by the complexity of the task: identifying an occupant's position, determining the position of solar beam radiation on interior room surfaces, determining the shading and reflection from interior furnishings, and determining the effect of solar altitude and azimuth on the occupant's non-cylindrical body shape.

On the other hand, designers are continually designing and specifying façades, fenestration, and shading systems, and it is important that they have a straightforward way to quantify the comfort consequences of different levels of solar radiation indoors. The solar variables that are under the designer's control are: the presence or absence of sunlight on the person, the extent of the person's body area exposed to direct sun, and the intensity of solar radiation after filtering through glass and window coverings. To evaluate comfort sufficiently early in design, the evaluation method should require minimal geometrical definition of interior architecture and workstation furnishings, since such details will often not be known at that stage.

This article describes how Standard 55-2017 evaluates the comfort consequences of direct solar radiation on occupants. It requires users to include the comfort impact of solar radiation whenever the representative occupant is exposed to direct beam solar. The standard offers both a prescriptive approach and performance calculation approach for complying with the new requirements, which are outlined in the next two sections.

Figure 1 (photo on facing page) illustrates a scenario in buildings where an occupant is exposed to direct sun, likely resulting in an uncomfortable thermal experience. Using the methods outlined in the Standard and discussed in the subsequent sections of this article, a designer can now calculate and determine that the occupant in *Figure 1* is experiencing the equivalent of increasing the mean radiant temperature (MRT) by 8.4°F (4.7°C) due to the impact of shortwave radiation. This will push him outside of the thermal comfort zone of occupants elsewhere in the space that are not in direct sun, making it difficult to maintain comfort for all occupants. The details of this example are provided in the next section.

Performance Calculation Approach

The performance calculation approach referenced in the new standard is stipulated in Normative Appendix C of the standard. The background for the calculations is described in detail in Reference 10. Thermal comfort is determined by six variables, four physical and two personal: mean radiant temperature, air temperature, air speed, relative humidity, clothing level, and metabolic rate. The impact of solar radiation on an occupant is calculated by equating the solar radiant energy flux on the body to a mean radiant temperature adjustment. The standard refers to this mean radiant adjustment factor as "shortwave mean radiant temperature," which is added to "longwave mean radiant temperature," where longwave MRT is the average space surface temperature weighted by occupant view factors. By splitting mean radiant temperature into shortwave and longwave components, the standard helps highlight the previously overlooked shortwave component and provides a simple method for calculating and including it in the overall mean radiant temperature determination.

The calculation method involves three steps:

1. Determine longwave mean radiant temperature $\left(t_{\overline{rlw}}\right)$.
2. Determine shortwave mean radiant temperature $\left(t_{\overline{rsw}}\right)$ using Normative Appendix C.
3. Mean radiant temperature $\left(t_{\bar{r}}\right)$ is equal to $\left(t_{\overline{rlw}} + t_{\overline{rsw}}\right)$ determined in Step 1 and Step 2.

The performance calculation approach is easily performed using the web-based CBE Thermal Comfort Tool[11,12] once the designer has some basic information about the glass and shade properties of the building. It has also been adopted within the Ladybug/Honeybee environmental analysis plugins for a commercial 3D modeling software.[13]

Definition of Input Values

The explanations below are a condensed version of what is available in the Standard. Refer to the Standard for more information.

Shortwave absorptivity (α_{SW}). The shortwave absorptivity of the occupant will range widely depending on the color of the occupant's skin, as well as the color and amount of clothing covering the body. A value is 0.7 shall be used unless more specific information about the clothing or skin color of the occupants is available.

Sky vault view fraction (f_{svv}). The sky vault view fraction ranges between 0 and 1 as shown in *Figure 2*. This value depends on the dimensions of the window (width w, height h) and the distance between the occupant and the window (d). f_{svv} is calculated using a formula provided in the Standard, and Table C2-2 of the Standard provides pre-calculated f_{svv} values for common situations.

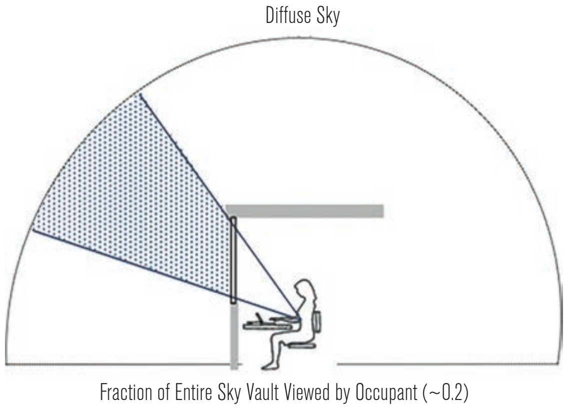


FIGURE 2 Fraction of sky vault in occupant's view (f_{svv}).

Total solar transmittance (T_{sol}). The total solar transmittance of window systems including glazing unit, blinds, and other façade treatments shall be determined using one of three methods provided in the Standard. One of the three approaches applicable to typical situations with interior fabric shades is: T_{sol} is the product of the Glazing Unit T_{sol} multiplied by the shade openness factor. Refer to the Standard for further guidance on this calculation and other methods.

Direct beam solar radiation (I_{dir}). Direct beam solar radiation data, which can be obtained from TMY and other standard weather data sources.

Fraction of the body exposed to solar beam radiation (f_{bes}). The fraction of the body's projected area factor (f_p) that is not shaded by the window frame, interior or exterior shading, or interior furniture. Refer to *Figure 3*.

Solar altitude (β). Solar altitude ranges from 0 degrees

Descriptions of the required inputs are given in *Table 1* and explained in the sidebar, "Definitions of Input Values."

Returning to our earlier example of the sunlit occupant in *Figure 1*, we can now understand the details of this scenario. This photo was taken in Oakland, Calif., at 4 p.m. in October and the inputs used to calculate the MRT adjustment are provided in the far column of *Table 1* and in *Figure 5* taken from the standard. The two resulting thermal comfort zones (Zone 1 does not account for direct solar and Zone 2 does) are shown on a psychrometric chart from the CBE Thermal Comfort Tool in *Figure 6*. One can imagine more extreme examples (e.g., height of summer in Houston), but this "mild" scenario provides insight into the extent of the effect of solar landing directly on an occupant. Because of the 8.4°F (4.7°C) increase in MRT, the room air temperature would need to be dropped to 70°F (21.1°C) to maintain comfort for this occupant. This would render the room's other, non-exposed occupants too cold, assuming they have similar metabolic rates and clothing levels.

Note that while our occupant does have a shade drawn in this scenario to deal with the glare, most shades do not block all solar radiation and create a hot radiant surface that must also be taken into account. The methods provided in the standard and explained in this article allow designers to account for shades (by adjusting T_{sol} and longwave MRT) and give full freedom to assess the scenarios. We can use the CBE MRT Calculator,[14] an open-source MRT model that includes the performance calculation approach for direct solar, to obtain a complete picture of comfort under both longwave and shortwave sources. *Figure 7* visualizes both the longwave and shortwave components of MRT seen in *Figure 1*. The longwave component shows the influence of the hot glass/shade assembly and the fact that the influence of the window on the MRT drops off quickly as the occupant moves further from the window. The shortwave component, however, is not greatly influenced by the

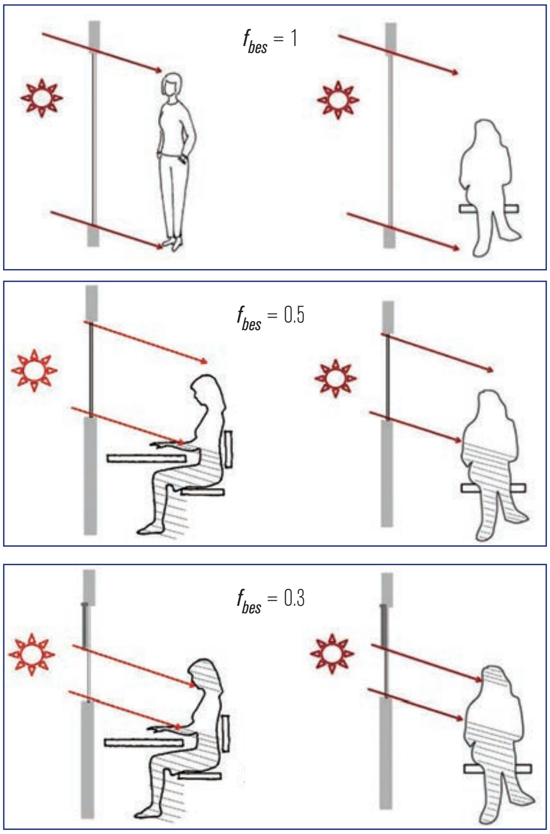


FIGURE 3 Fraction of body exposed to sun (f_{bes}), not including the body's self-shading. It is acceptable to simplify f_{bes} to equal the fraction of the distance between head and toe exposed to direct sun, as shown.

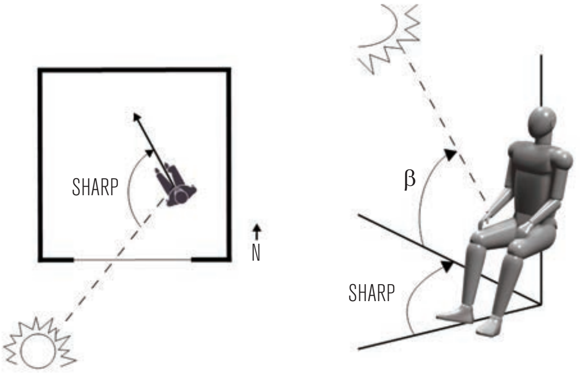


FIGURE 4 Solar horizontal angle relative to the front of the person (SHARP).

(horizon) to 90° (zenith). Also called solar elevation. See *Figure 3*.

Solar horizontal angle relative to the front of the person (SHARP). Solar horizontal angle relative to the front of the person ranges from 0° to 180° and is symmetrical on either side. 0° represents direct beam radiation from the front, 90° represents direct beam radiation from the side, and 180° represent direct beam radiation from the back. SHARP is the angle between the sun and the person only. Orientation relative to compass or to room are not included in SHARP. See *Figure 4*.

Posture. Inputs are "seated" and "standing."

distance from the window because only the sky vault view fraction component of the shortwave MRT calculation is affected by distance to the window. In other words, there will be a significant shortwave component as far as the direct sun is able to penetrate into the space.

TABLE 1 Input variables and Ranges for calculation procedure.

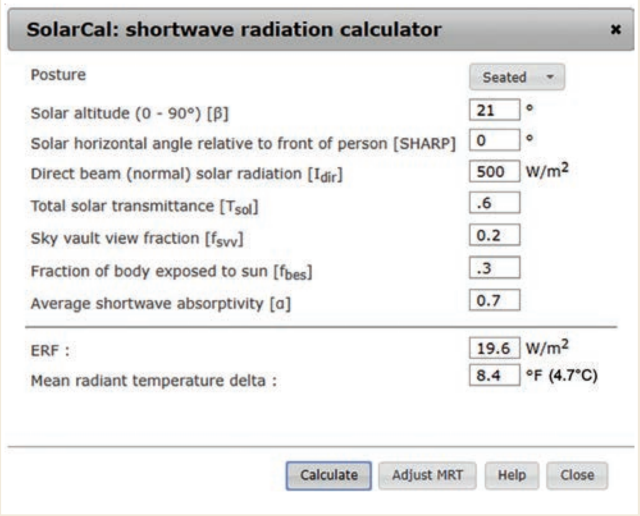
SYMBOL	DESCRIPTION	UNIT	ALLOWABLE DEFAULT VALUE	RANGE OF INPUTS MIN. – MAX.	*FIGURE 1* INPUTS
α_{sw}	Shortwave Radiation Absorptivity	–	0.7	0.2 – 0.9	0.7
f_{svv}	Fraction of Sky Vault Exposed to Body	–	N/A	0 – 1	0.2
T_{sol}	Window System Glazing Unit Plus Shade Solar Transmittance	–	N/A	0 – 1	0.6 (Tinted Single Pane Glass)
I_{dir}	Direct Solar Beam Intensity	W/m^2	900	200 – 1000	500 (Oakland, October, 4 p.m.)
f_{bes}	Fraction of the Possible Body Surface Exposed to Sun	–	N/A	0 – 1	0.3
β	Solar Altitude Angle	Degree	N/A	0 – 90	21 (Oakland, October, 4 p.m.)
SHARP	Solar Horizontal Angle Relative to Person	Degree	N/A	0 – 180	5
	Posture (Seated, Standing)		N/A	Seated/Standing	Seated

Prescriptive Approach

Designers can also comply by meeting the standard's prescriptive requirements. The prescriptive approach allows the designer to simply use a mean radiant temperature $\left(\bar{t}_r\right)$ that is 5°F (2.8°C) higher than average air temperature (t_a) under some typical conditions. The simplified method applies when all of the following conditions are met.

1. A space with air temperature stratification less than Section 5.3.4.3 in the standard.
2. A space without active radiant surfaces.
3. Building envelope opaque surfaces of the space (walls, floor, roof) meet U-value prescriptive require-

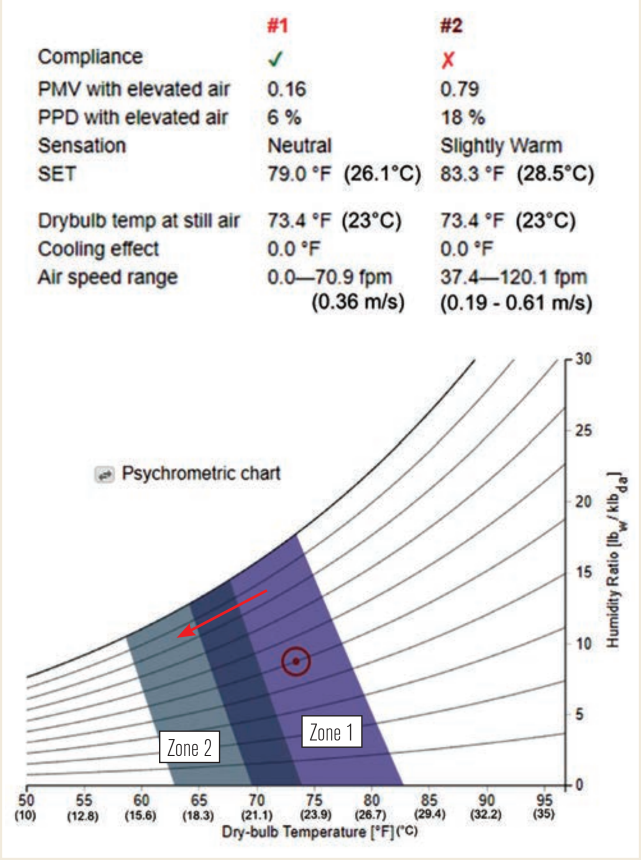
FIGURE 5 Comfort tool inputs for *Figure 1* example.



SolarCal: shortwave radiation calculator

Posture	Seated
Solar altitude (0 - 90°) [β]	21 °
Solar horizontal angle relative to front of person [SHARP]	0 °
Direct beam (normal) solar radiation [I_{dir}]	500 W/m²
Total solar transmittance [T_{sol}]	.6
Sky vault view fraction [f_{svv}]	0.2
Fraction of body exposed to sun [f_{bes}]	.3
Average shortwave absorptivity [α]	0.7
ERF :	19.6 W/m²
Mean radiant temperature delta :	8.4 °F (4.7°C)

FIGURE 6 Comfort zones of two conditions: Zone 1 is the comfort zone while not in direct sun; Zone 2 is the comfort zone while in direct sun. The comfort zone shifts left (colder air temperature required) when in direct sun, and the occupant's condition (red dot) ends up out of the comfort zone. Note that the ambient MRT in both zones is 80°F (26.7°C). Zone 2 adds only the 8.4°F (4.7°C) shortwave-adjusted MRT for sunlight on the occupant's body.



	#1	#2
Compliance	✓	✗
PMV with elevated air	0.16	0.79
PPD with elevated air	6 %	18 %
Sensation	Neutral	Slightly Warm
SET	79.0 °F (26.1°C)	83.3 °F (28.5°C)
Drybulb temp at still air	73.4 °F (23°C)	73.4 °F (23°C)
Cooling effect	0.0 °F	0.0 °F
Air speed range	0.0—70.9 fpm (0.36 m/s)	37.4—120.1 fpm (0.19 - 0.61 m/s)

ment of ASHRAE/IES Standard 90.1.

4. Outdoor air temperature is less than 110°F (43°C).
5. Vertical fenestration has less than 9 ft (3 m) total height.
6. No skylights are present.
7. The space complies with all requirements in a single row of Tables 5.3.2.2.1 A, B, C or D. Interpolation between values within a single table (5.3.2.2.1A, B, C or D), but not between tables, is permissible. Solar absorptance properties for shade fabrics used in Tables 5.3.2.2.1A, B, C or D shall use the most similar color from Table 5.3.2.2.1E unless more specific data is available from the manufacturer.

Basis of the Prescriptive Approach

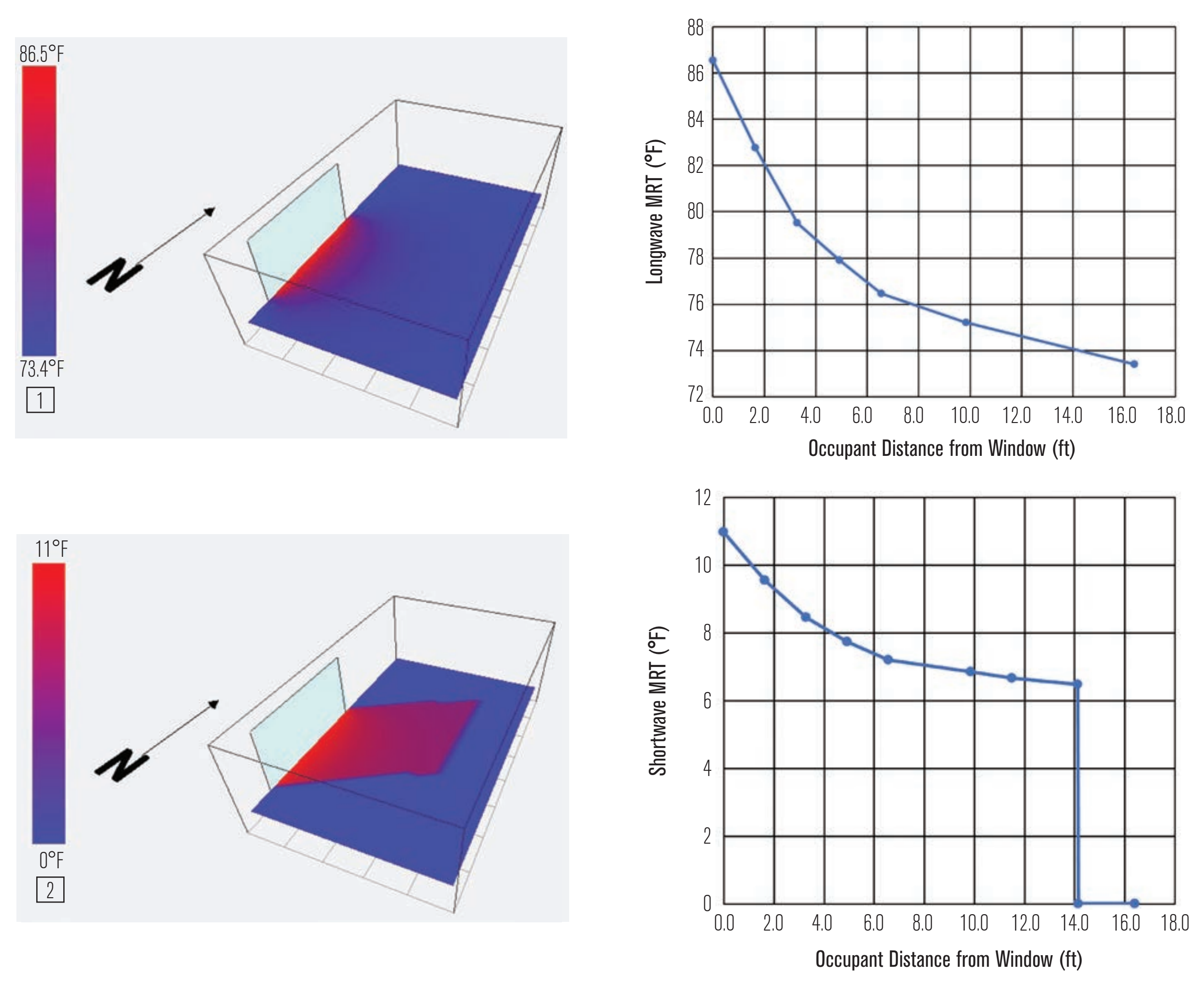
The prescriptive approach exemplifies the details and importance of accounting for direct solar exposure on occupants. It is inherently conservative because it limits the impact of solar radiation to a shift of half the comfort zone (e.g., from 0 to +0.5 PMV, which represents roughly 6°F (3.3°C) shift in air temperature.). This range allows two occupants in the same building thermal zone, one in the sun and one not in the sun, to both be comfortable given the same values for the other five thermal comfort variables. If one wished to make use of the full comfort zone and use more aggressive assumptions, one would use the standard's analytical approach described previously.

Working backwards from this PMV shift, along with a set of conservative assumptions, the standard is able to provide tables of window and shade combinations that will maintain occupant comfort given Standard 90.1 prescriptive envelope construction. (See sidebar, "Prescriptive Approach Tables.") The prescriptive approach tables incorporate very conservative assumptions to ensure comfort is maintained even in the worst indoor conditions.

- Occupant azimuth: 0° (directly facing window);
- Direct beam normal radiation: 900 W/m² (285 Btu/h·ft²);
- Solar azimuth: 270°;
- Solar altitude standing: 30° (worst case angle);
- Solar altitude seated: 50° (worst case angle);
- Large west-facing glass wall (49 ft wide by 10 ft high [15 m wide by 3 m high]); and
- 110°F (43°C) outside temperature (higher than NFRC Summer rating condition).

The prescriptive tables were generated by iterating on glass assembly properties (including interior shading), and the occupant distance from the window, to achieve

FIGURE 7 MRT Calculator visualization of (1) longwave MRT and (2) shortwave ΔMRT. The combined MRT that the occupant experiences is the sum of the longwave and shortwave MRT; thus 5 ft (1.5 m) from the window, the MRT would be 85.6°F (29.8°C).



the required criterion of ΔPMV < 0.5. Two tools were used to develop to Standard 55 prescriptive tables: LBNL WINDOW[15] and CBE MRT Calculator.[14] LBNL WINDOW was used to determine the inside surface temperature of the glass wall + shade next to the occupant in order to account for the longwave contribution of the hot window/shade surface. The CBE MRT Calculator was used to obtain the combined effects of both longwave and shortwave radiation on occupant PMV (as shown in previous example in *Figure 7*).

The prescriptive tables of glass and shade combinations are meant to cover typical new and existing building windows, but they are clearly not exhaustive. The tables highlight the tradeoffs in glass properties that affect the comfort of the occupants. While the MRT shift associated with direct solar is most directly linked to the T_{sol} property of the window/shade assembly, glass with lower T_{sol} is typically tinted and thus absorbs more solar radiation, meaning the glass becomes hot and reradiates some of that energy into the space, increasing long wave mean radiant temperature and overall MRT. A shade that is light-colored on its outside surface helps to reflect solar energy, resulting a low T_{sol} as well as a low inside surface temperature compared to a dark shade of the same openness factor (as captured by "Interior Shade Solar Absorptance" in the tables). Additionally, SHGC plays a role in T_{sol} and helps separate high performance spectrally selective glazing from other low-e glazing. The "indirect SHGC" referenced in the tables provides a better metric for separating out broad categories of glass types than SHGC alone.[7]

One key takeaway from the prescriptive tables is the requirement for interior shading in all cases, with the exception of electrochromic glazing units in darker states. It is worth noting that the amount of shading

Prescriptive Approach Tables

Tables 5.3.2.2.1A and B (from Standard 55-2017) show criteria that allow use of mean radiant temperature $(\bar{t}_r)$ that is 2.8°C (5°F) higher than average air temperature (t_a) for high-performance glazing units (Table 5.3.2.2.1A), and for clear low performance glazing units (Table 5.3.2.2.1B). Standard 55-2017 also has tables for tinted glazing units and electrochromic glazing units. Table 5.3.2.2.1E provides absorptance values for typical shade colors.

Table 5.3.2.2.1A High-performance (low-e, double pane) glazing units.

Representative Occupant Distance from Interior Window or Shade Surface, ft	Fraction of Body Exposed to Sun (f_{bes}), %	Glazing Unit Total Solar Transmission, (T_{sol}), %	Glazing Unit Indirect SHGC (SHGC – T_{sol}), %	Interior Shade Openness Factor, %	Interior Shade Solar Absorptance Of Window-Facing Side, %
≥3.3	≤50	≤35	≤4.5	≤9	≤65
≥3.3	≤100	≤35	≤4.5	≤5	≤65

Table 5.3.2.2.1B Clear low-performance glazing units.

Representative Occupant Distance from Interior Window or Shade Surface, ft	Fraction of Body Exposed to Sun (f_{bes}), %	Glazing Unit Total Solar Transmission, (T_{sol}), %	Glazing Unit Indirect SHGC (SHGC - T_{sol}), %	Interior Shade Openness Factor, %	Interior Shade Solar Absorptance Of Window-Facing Side, %
≥9.9	≤50	≤83	≤10	≤1	≤25
≥13.2	≤50	≤83	≤10	≤1	≤65
≥11.2	≤100	≤83	≤10	≤1	≤25
≥14.5	≤100	≤83	≤10	≤1	≤65

Table 5.3.2.2.1E Interior shade solar absorptance based on color description of window-facing side of shade.

Solar Absorptance, %	<15	15 – 25	25 – 65	>65
Color Description	White	Silver, Cornsilk, Wheat, Oyster, Beige, Pearl	Beige, Pewter, Smoke, Pebble, Stone, Pearl Grey, Light Grey	Charcoal, Graphite, Chestnut

required for thermal comfort with high-performance glazing is less than that typically specified for visual comfort (glare control) near windows exposed to direct sunlight, which generally require a maximum openness factor of 3%.[15] However, with low-performance glazing (e.g., single pane retrofit applications), the openness factor is severely curtailed (<1%) and even then thermal comfort is not maintained 3.3 ft (1 m) from the window. Well-designed exterior sunshades will reduce or eliminate the requirement for interior shades, which have high surface temperature and inward radiation resulting from the sunlight they intercept.

A second key takeaway from the prescriptive tables is the distance an occupant must be away from windows to stay under the prescriptive limit, illustrated in the clear low-performing glazing unit table. For the glass types shown in this table with a 1% open shade, the occupant must be 9.9 to 14.5 ft (3.0 to 4.4 m) away from the window to stay under the prescriptive limit (range varies based on interior shade color). This new calculation method in the standard can now quantify the "uncomfortable" zone at the perimeter of existing buildings with low-performing glazing that existed when they were constructed. Perimeter zone discomfort in existing buildings is well documented.

Conclusion

Standard 55-2017 now includes a method and associated web-based software tools to quantify and evaluate the effect of direct solar radiation on occupants in buildings. The steps in the analysis leading to compliance provide valuable guidance to architectural and engineering design teams deciding on façade choices and interior window treatments. The analysis steps provide a more complete view of the impact of façade design on indoor comfort and on HVAC requirements. In time they should increase the use of simulation tools such as LBNL's WINDOW for predicting solar transmission and interior surface temperatures in complex window systems, and other tools such as the CBE MRT Calculator that maps MRT as experienced by occupants within rooms, coming from both longwave and shortwave radiation sources. To simplify application of the new method in typical scenarios, the new standard provides a prescriptive compliance path that uses easily accessible window and interior shade properties. The prescriptive compliance path ensures occupant comfort in all climates and in worst-case conditions of occupant exposure to sunlight and building geometry.

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