IEQ and Thermal Comfort: The Next Energy Efficiency Frontier?

Brian Just

IAQ & Energy 2020 CONFERENCE

Overview

- Why we’re here
- ASHRAE 55: Theory
- ASHRAE 55: Application
- Tools beyond ASHRAE
- Designing for comfort
- Beyond ASHRAE…
- Pulling it all together

Why we’re here

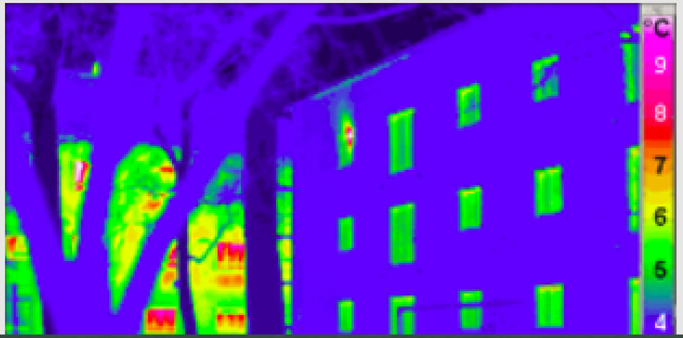
Why we're here

Half of Americans Surveyed Struggle to Feel Warm and Comfortable in their Homes During the Winter Months Finds RPA|Ecocor

Drafts and Poor Insulation Create Both Discomfort and Familial Strife

MILFORD, PA AND SEARSMONT, ME (PRWEB) DECEMBER 07, 2016

Richard Pedranti Architect (RPA), a full-service architecture firm focused on sustainable design, and Ecocor, a construction company that manufactures, delivers and assembles high performance Passive House buildings, surveyed Americans and found that regardless of how much they pay to heat their home, more than half of respondents struggle to feel comfortable in



Ref: http://www.prweb.com/releases/2016/12/prweb13906216.htm

Why we're here

"The most common complaint facility managers hear from building occupants is that their office space is too cold.

That would seem an easy enough problem to solve, except for the fact that the number two complaint is that it's too hot."

Ref:*Expanding the Engineers' Comfort Zone: Working with Adaptive Thermal Comfort*, BuildingGreen, 2004, https://www.buildinggreen.com/feature/expanding-engineers-comfort-zone-working-adaptive-thermal-comfort

IEQ = Indoor Environmental Quality

IEQ = IAQ +ITQ + ILQ + ISQ + IOQ + IVQ

where **I** = Indoor, **Q** = Quality

and
A = Air
T = Thermal
L = Lighting
S = Sound
O = Odor
V = Vibrations

Much more to comfort than just thermal!

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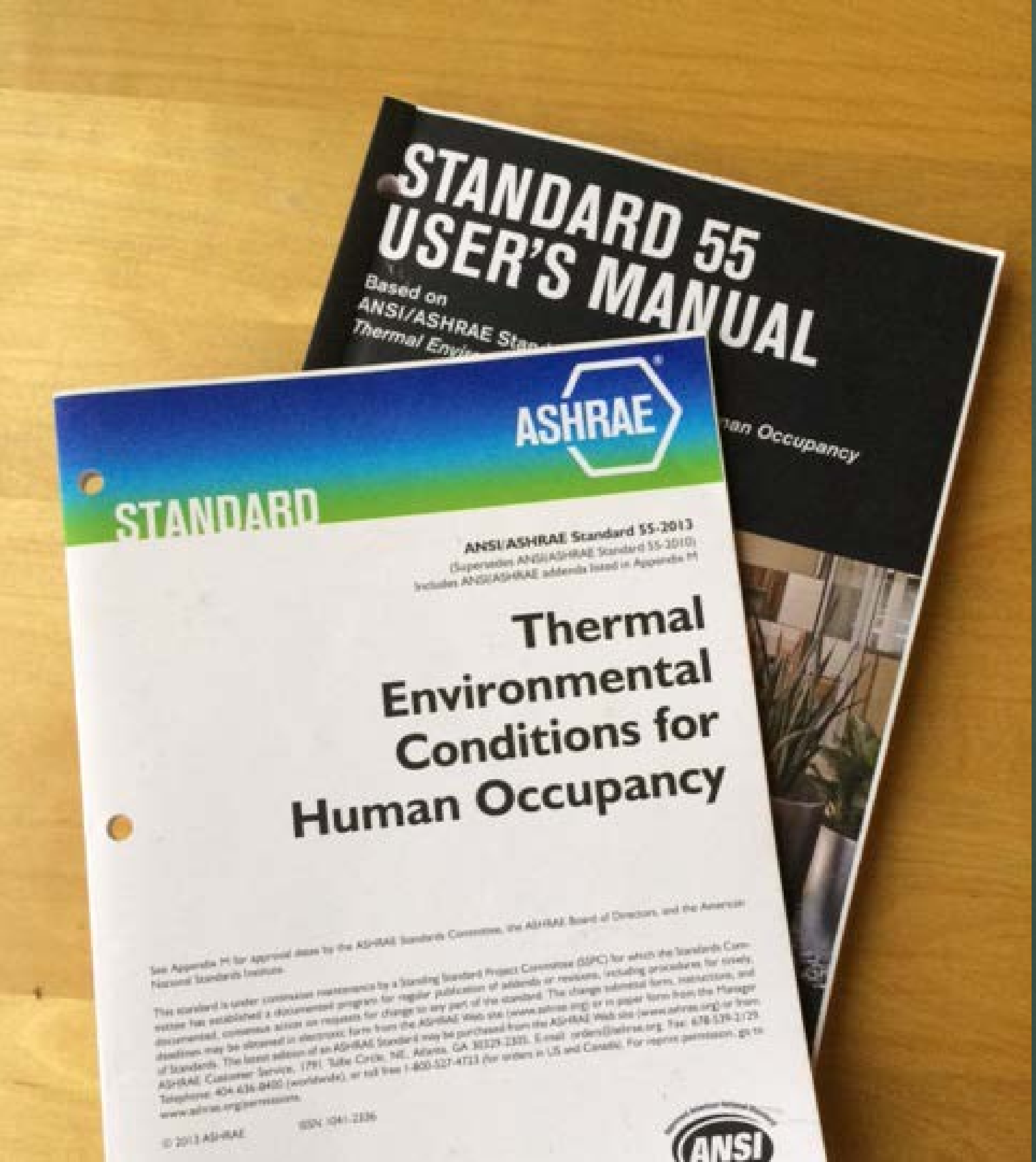
Ref: *Definition of Indoor Environmental Quality (IEQ),* Healthy Heating, http://www.healthyheating.com/Defintion_of_indoor_environmental_quality.htm#.WrEB7WobOUv

ASHRAE 55: Theory



ASHRAE 55

The science of comfort (sort of)

Purpose: "…to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space."

Thermal comfort: 6 factors

- Metabolic rate (met)
- Clothing insulation (clo)
- Air temperature
- Radiant temperature
- Air speed
- Humidity

Personal factors: Metabolic rate, Clothing insulation

Environmental factors: Air temperature, Radiant temperature, Air speed, Humidity

Thermal comfort: 6 factors

- Metabolic rate (met)
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- Air temperature
- Radiant temperature
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Personal factors (Metabolic rate, Clothing insulation)

Environmental factors (Air temperature, Radiant temperature, Air speed, Humidity)

Personal factor #1: Metabolic rate

TABLE 5.2.1.2 Metabolic Rates

Activity	Met Units
Resting	
Sleeping	0.7
Reclining	0.8
Seated, quiet	1.0
Standing, relaxed	1.2
Walking (on level surface)	
0.9 m/s, 3.2 km/h, 2.0 mph	2.0
1.2 m/s, 4.3 km/h, 2.7 mph	2.6
1.8 m/s, 6.8 km/h, 4.2 mph	3.8
Office Activities	
Reading, seated	1.0
Writing	1.0
Typing	1.1

Personal factor #2: Clothing insulation

TABLE 5.2.2.2B Garment Insulation (I_{clu})

Garment Description[a]	I_{clu}(clo)	Garment Description[a]	I_{clu}(clo)
Underwear		Dress and Skirts[b]	
Bra	0.01	Skirt (thin) mm	0.14
Panties	0.03	Skirt (thick)	0.23
Men's briefs	0.04	Sleeveless, scoop neck (thin)	0.23
T-shirt	0.08	Sleeveless, scoop neck (thick), i.e., jumper	0.27
Half-slip	0.14	Short-sleeve shirtdress (thin)	0.29
Long underwear bottoms	0.15	Long-sleeve shirtdress (thin)	0.33
Full slip	0.16	Long-sleeve shirtdress (thick)	0.47
Long underwear top	0.20	Sweaters	
Footwear		Sleeveless vest (thin)	0.13
Ankle-length athletic socks	0.02	Sleeveless vest (thick)	0.22
Panty hose/stockings	0.02	Long-sleeve (thin)	0.25
Sandals/thongs	0.02	Long-sleeve (thick)	0.36
Shoes	0.02	Suit Jackets and Vests[c]	
Slippers (quilted, pile lined)	0.03	Sleeveless vest (thin)	0.10

Personal factor #2: Clothing insulation

TABLE 5.2.2.2A Clothing Insulation (I_{cl}) Values for Typical Ensembles

Clothing Description	Garments Included*	I_{cl} (clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.96
	4) #2 plus suit jacket, vest, T-shirt	1.14
	5) #2 plus long-sleeve sweater, T-shirt	1.01
	6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	9) Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater	1.10
	10) Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13) Long-sleeve coveralls, T-shirt	0.72
	14) Overalls, long-sleeve shirt, T-shirt	0.89

Thermal comfort: 6 factors

- Metabolic rate (met)
- Clothing insulation (clo)
- Air temperature
- Radiant temperature
- Air speed
- Humidity

Personal factors

Environmental factors

Envir. factor #1: Air temperature

- The most obvious
- Most thermostats do this (and only this)

Envir. factor #1: Air temperature

- The most obvious
- Most thermostats do this (and only this)
- “Universal compensator” for the other 5 variables (personal and environmental)

Envir. factor #2: Radiant temperature

- The “hot” and “cold” of surrounding surfaces can make you uncomfortable!
- This is why it’s possible to feel cold in a 72F room when seated near a cool window or wall

Envir. factor #2: Radiant temperature

Implications:

- Poor windows and cold walls have real comfort impacts
- It’s also why radiant or insulated floors can help even if air temp isn’t necessarily high

Mean Radiant Temperature (MRT) is a measurement that takes surrounding surfaces into account (weighted average surrounding a single point)

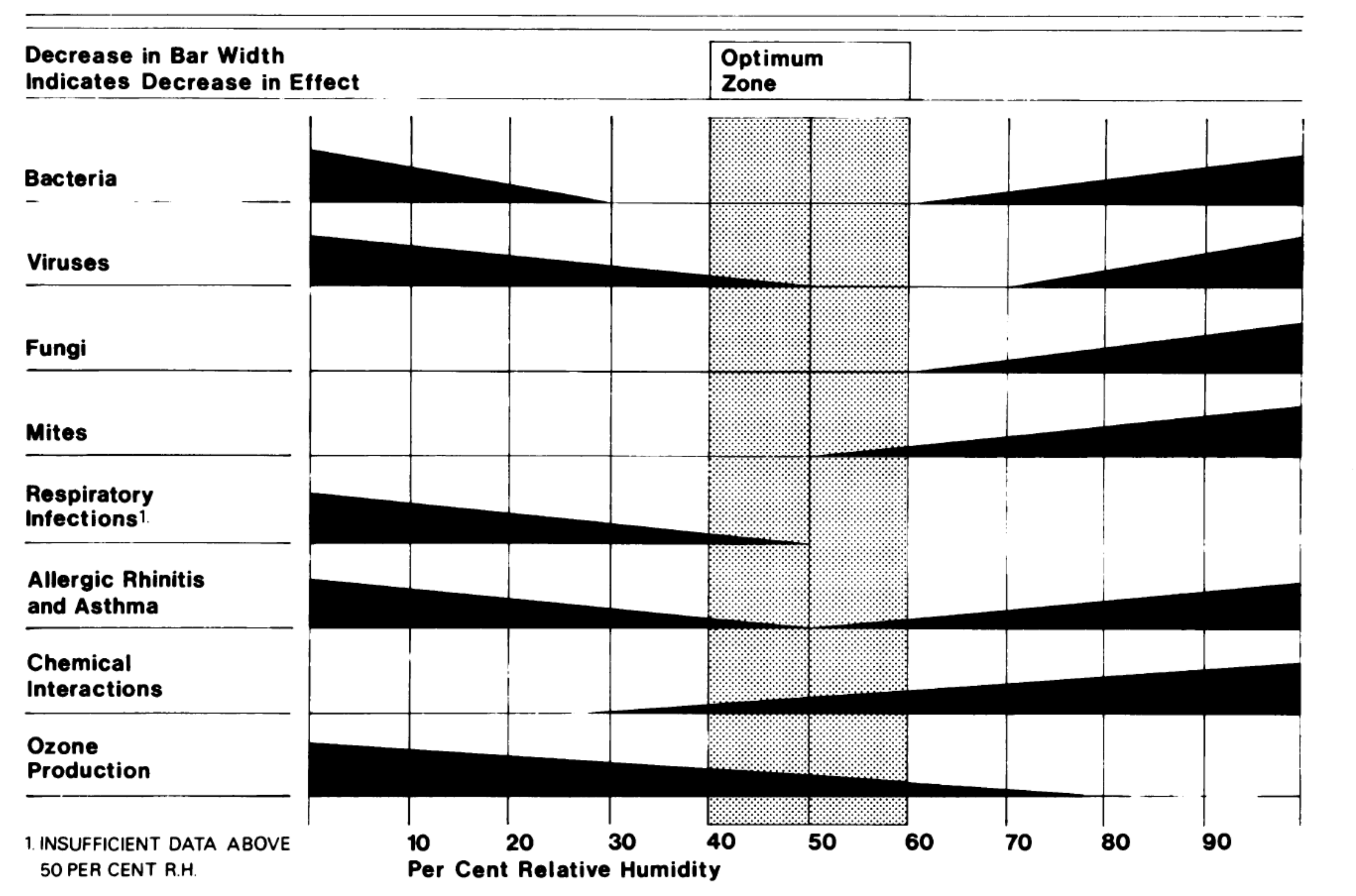
Envir. factor #3: Humidity

Sterling chart –

Useful but take with a grain of salt

A decent target: 40%

Ref: [Humidity, Health, and the Sterling chart](), Energy Vanguard



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Envir. factor #3: Humidity

And more…

why control rh between 35% & 55% (+/-5%)

to control hydrolysis (VOC emissions)

to control microbial (virus, bacteria, molds, mites, some insects)

to enable comfort in mucous membranes (respiratory, eyes (skin))

to support hydration (affects cognition and wound healing)

to enable positive perceptions of thermal comfort

to enable positive perceptions of indoor air quality

to enable positive perceptions of indoor odour quality

to maintain dimensional stability in hygroscopic materials (woods)

to prevent condensation on hydrophobic materials (glass)

to prevent condensation in hydrophilic materials (drywall)

to preserve moisture sensitive artifacts / collectibles / musical instruments

Courtesy Robert Bean
http://www.healthyheating.com/

Envir. factor #4: Air motion

- Good for delivery and mixing
- However, it *can* be bad when
  - In winter, cool moving air that's more than 3F below room temperature*
  - Velocities greater than 30 fpm*

*Per ASHRAE 55

Other definitions

Dry bulb temperature

- "Air temperature" (typ.) – shielded from radiation and moisture

Wet bulb temperature

- Temperature a parcel of air would have if it were cooled to saturation (100% RH) by evaporation of water into it, with latent heat supplied by the parcel
- At 100% RH, wet bulb temp = dry bulb temp
- Sling psychrometer

Other definitions

Operative temperature

- T_{op} = ½ dry bulb + ½ MRT

We'll see this a lot…

ASHRAE 55 comfort framework

PMV and PPD

PMV = Predicted Mean Vote

- ASHRAE scale (subjective)
- “Comfort zone” defined as *-0.5 PMV to +0.5 PMV*

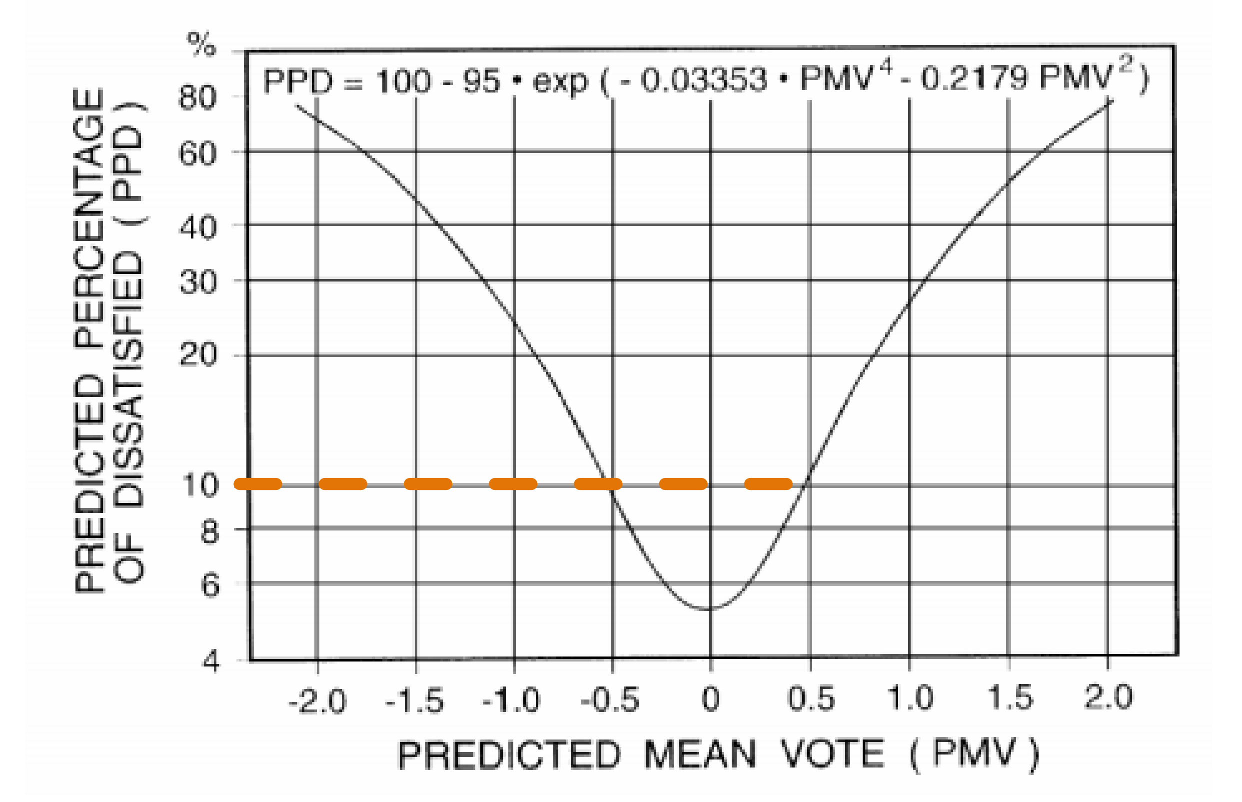
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
–1	Slightly cool
–2	Cool
–3	Cold

PPD = Predicted Percentage Dissatisfied

- People voting |2| or greater

Empirical model *-0.5 PMV to +0.5 PMV* predicts 90% of population satisfied, or 10% PPD

PMV and PPD



Ref: http://ceae.colorado.edu/~brandem/aren3050/docs/ThermalComfort.pdf

Local discomfort

We want to avoid:

1. Radiant temperature asymmetry
   - Ceiling ≥ 9F warmer than floor
   - Ceiling ≥ 14F cooler than floor
   - Wall ≥ 41F warmer than air
   - Wall ≥ 18F cooler than air
2. Draft
   - If clo < 0.7, met < 1.3, and T_{op} < 72.5F, keep < 30 fpm
   - Upper limit is 240 fpm with right conditions

Local discomfort

We want to avoid:

3. Vertical air temperature difference
   - Head and ankle difference < 5.4F
4. Floor surface temperature too hot or too cold
   - Comfort range *while wearing shoes* is 66.2 - 84.2F
5. Temperature variation with time
6. Cyclic variations, drifts, and ramps
   - Operative temperature should vary
     - Within 2F if cycling within a 15-minute period
     - Within 4F over 1-hour period

Huh?

Bottom line =

- This is about occupants and it’s subjective
- The target is to keep 80% of people happy
- There *are* some “hard” guidelines
- **…and there are real implications with significant overlap with energy efficiency**

Thank you,
Ole Fanger.

Now…let's see
how to use this.

ASHRAE 55: Application

Primary tools

1. Graphical method (chart)
2. Software method

   (CBE Thermal Comfort tool, https://comfort.cbe.berkeley.edu/)

Example: Brian's house in winter (graphical method)

- Thermostat 66F
- RH 30%
- Clo = 0.90 (typ. winter outfit)
- Met = 1.0 (seated, reading)

T_{op} = ½ dry bulb + ½ MRT

= ½ 66F + ½ ?? (don't know…yet)

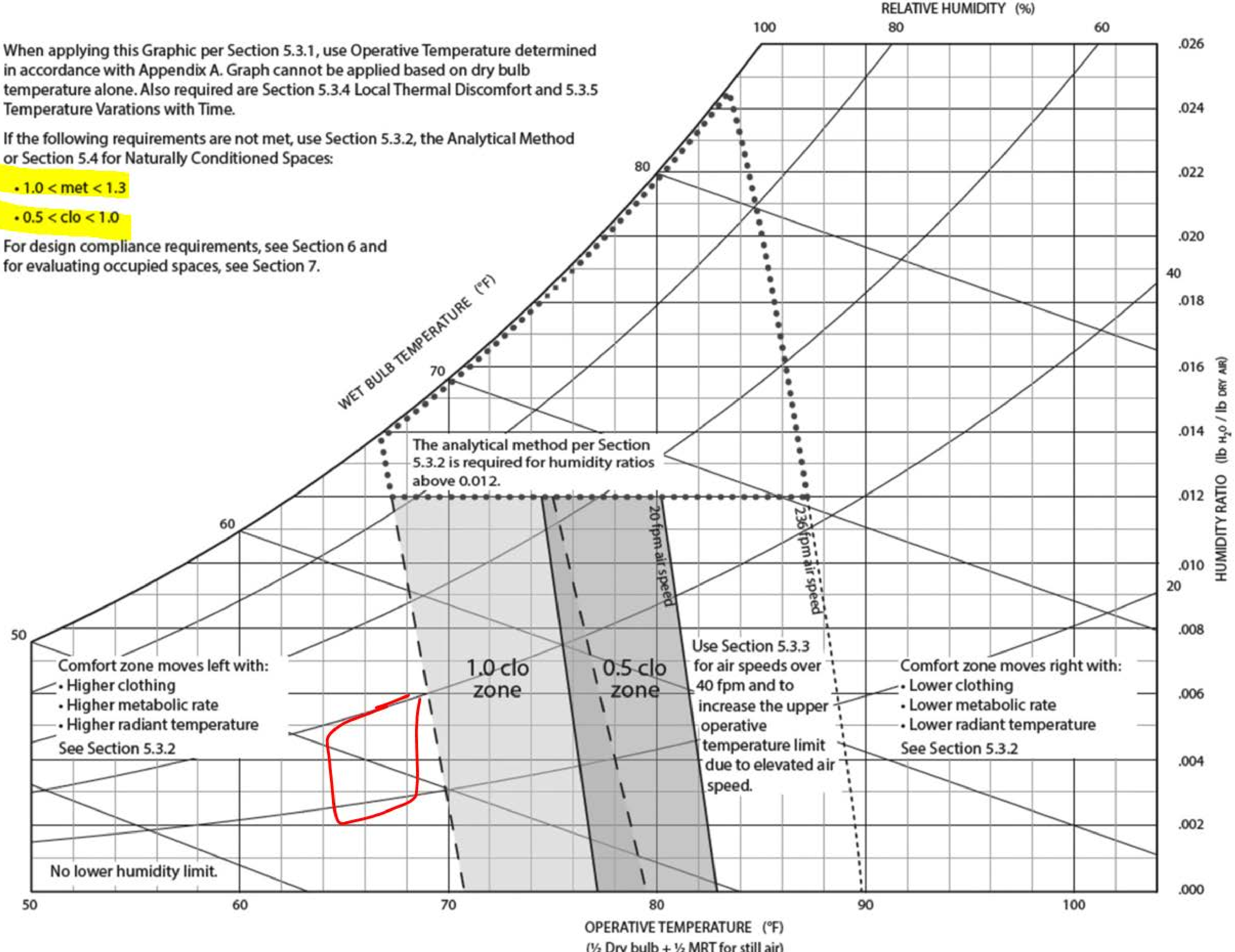
= For now, assume it's about 66F

When applying this Graphic per Section 5.3.1, use Operative Temperature determined in accordance with Appendix A. Graph cannot be applied based on dry bulb temperature alone. Also required are Section 5.3.4 Local Thermal Discomfort and 5.3.5 Temperature Varations with Time.

If the following requirements are not met, use Section 5.3.2, the Analytical Method or Section 5.4 for Naturally Conditioned Spaces:

- 1.0 < met < 1.3
- 0.5 < clo < 1.0

For design compliance requirements, see Section 6 and for evaluating occupied spaces, see Section 7.



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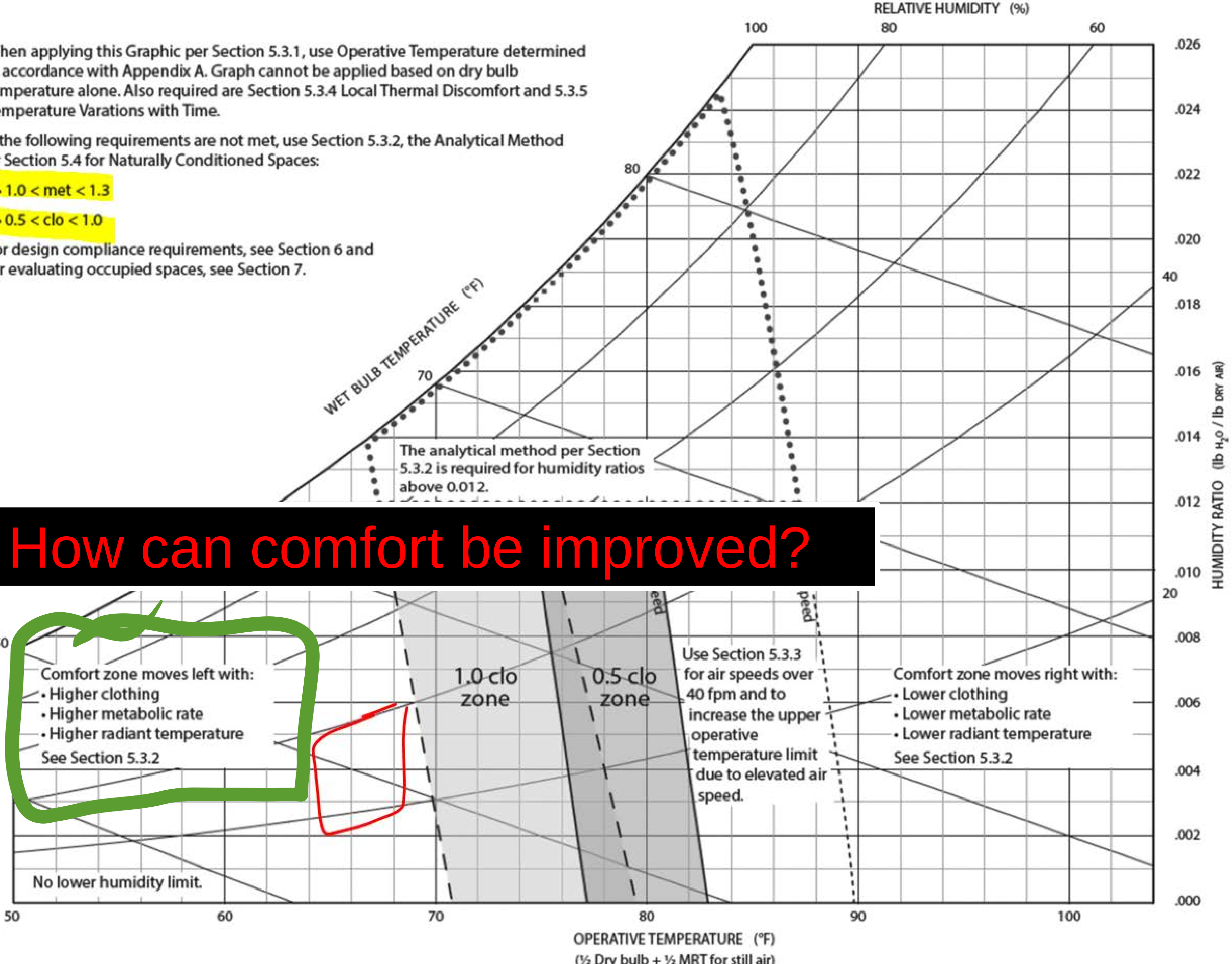
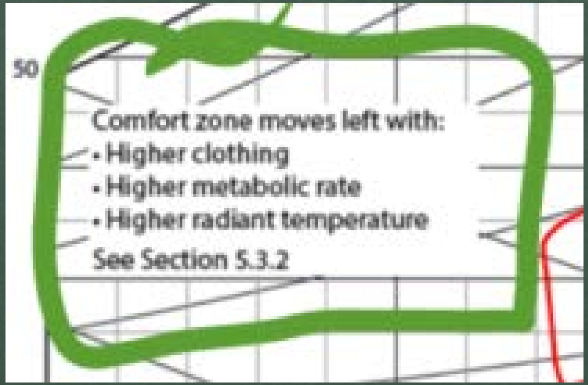
How can comfort be improved?



Example: Brian's house in winter (graphical method)

Tools for improving comfort when cold:

- Higher clothing
- Higher metabolic rate
- Higher MRT



- But if we tweak these too much, we're easily pushing off the "valid" scale of the chart – so we need another tool

If the following requirements are not met, use Section 5.3.2, the Analytical Method or Section 5.4 for Naturally Conditioned Spaces:

- $1.0 < met < 1.3$
- $0.5 < clo < 1.0$

Example: Brian's house in winter (software method)

- Thermostat 66F
- RH 30%
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= ½ 66F + ½ ?? (don't know…yet)

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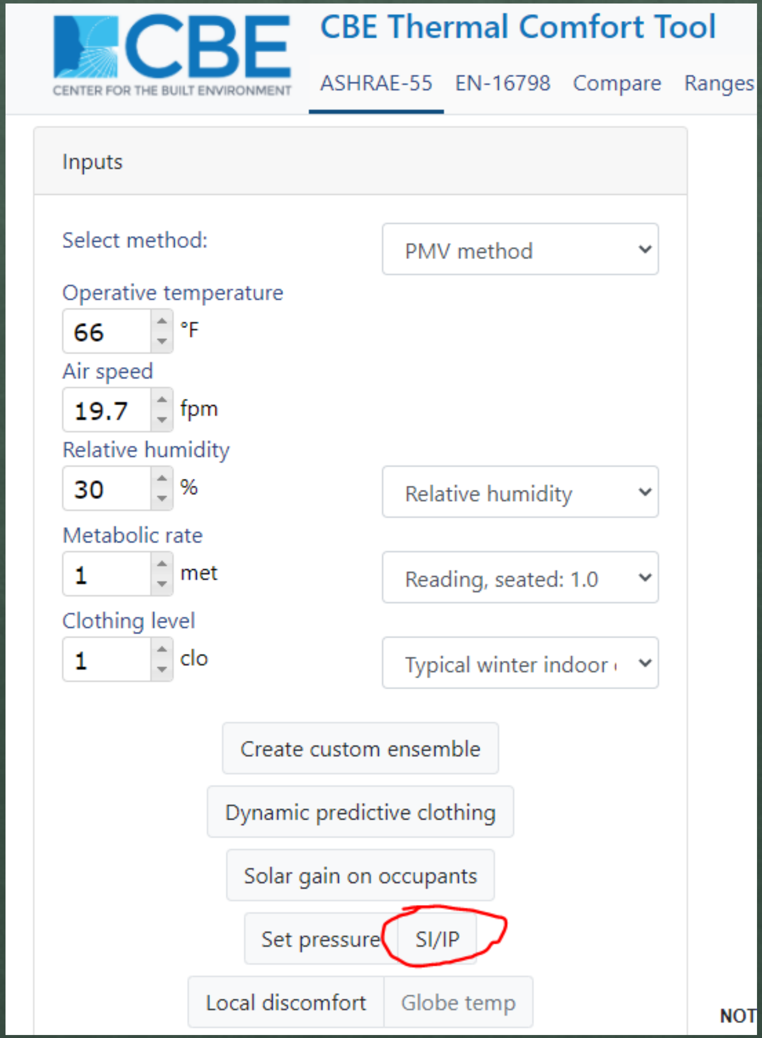
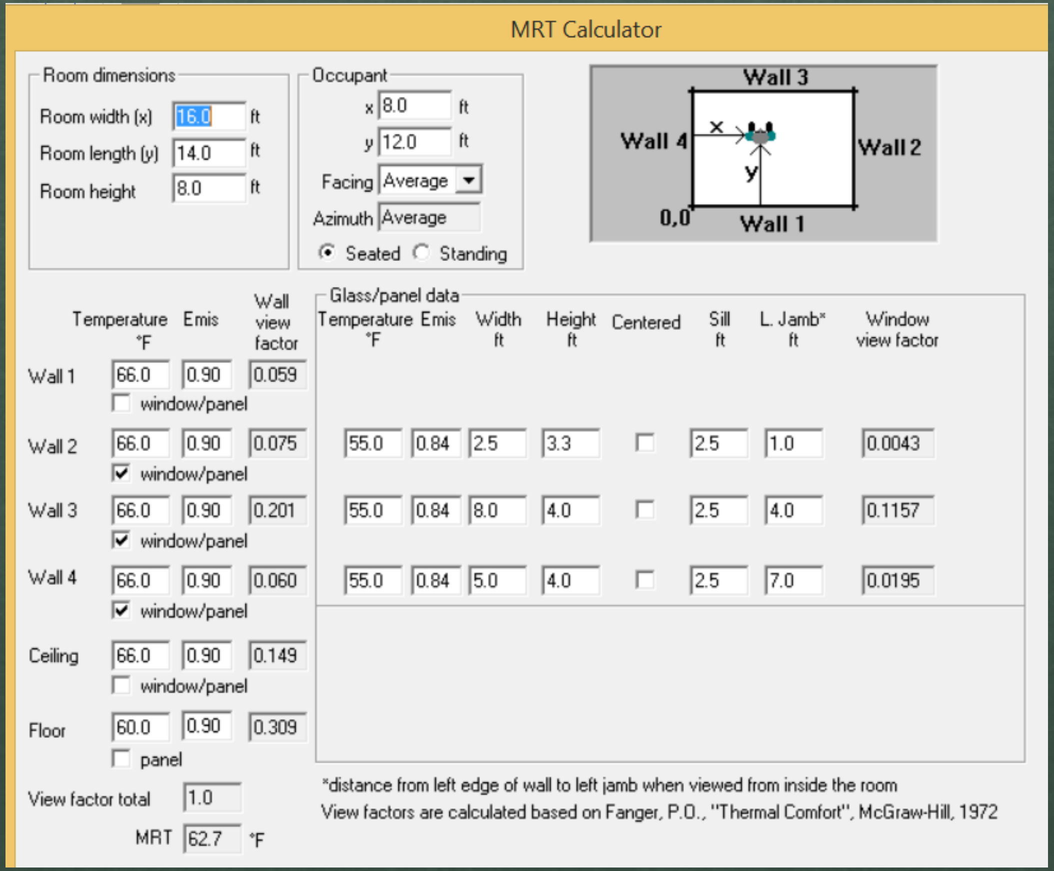


Example: Calculating MRT

Remember, this is simply combining all the temperatures around you into a single value

1. Obsolete ASHRAE software ➔
2. Somewhat tedious, metric-only free online software http://centerforthebuiltenvironment.github.io/mrt/
3. Back of the envelope



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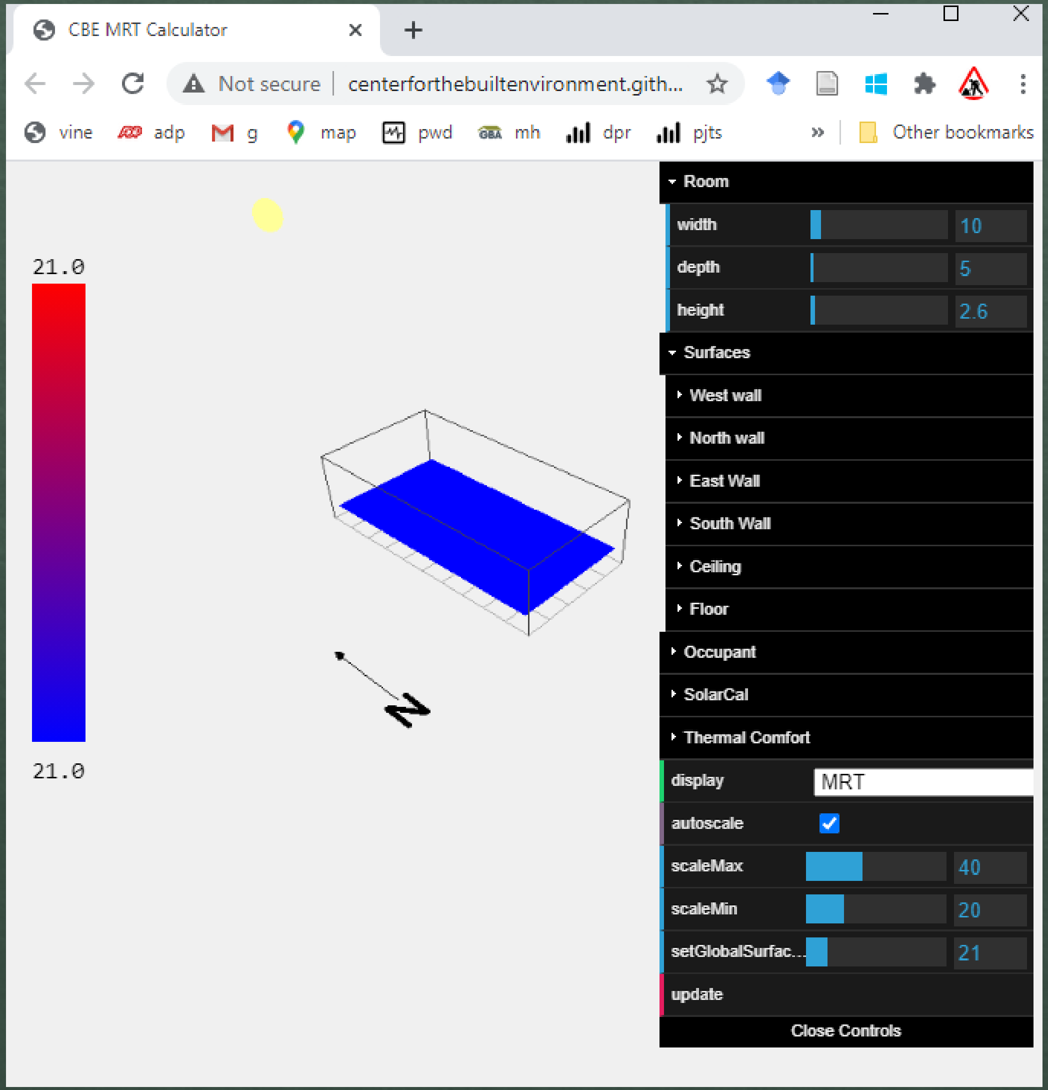

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3. Back of the envelope ➔

Standing in middle of a huge room:

- 30% exposure to 60F floor
- 30% exposure to 66F ceiling
- 35% exposure to 66F walls
- 5% exposure to 55F windows

MRT = 0.30*60F + 0.30*66F + 0.35*66F + 0.05*55F = 63.65F

Sitting 2' from a window in a living room:

- 30% exposure to 60F floor
- 15% exposure to 66F ceiling
- 40% exposure to 66F walls
- 15% exposure to 55F windows

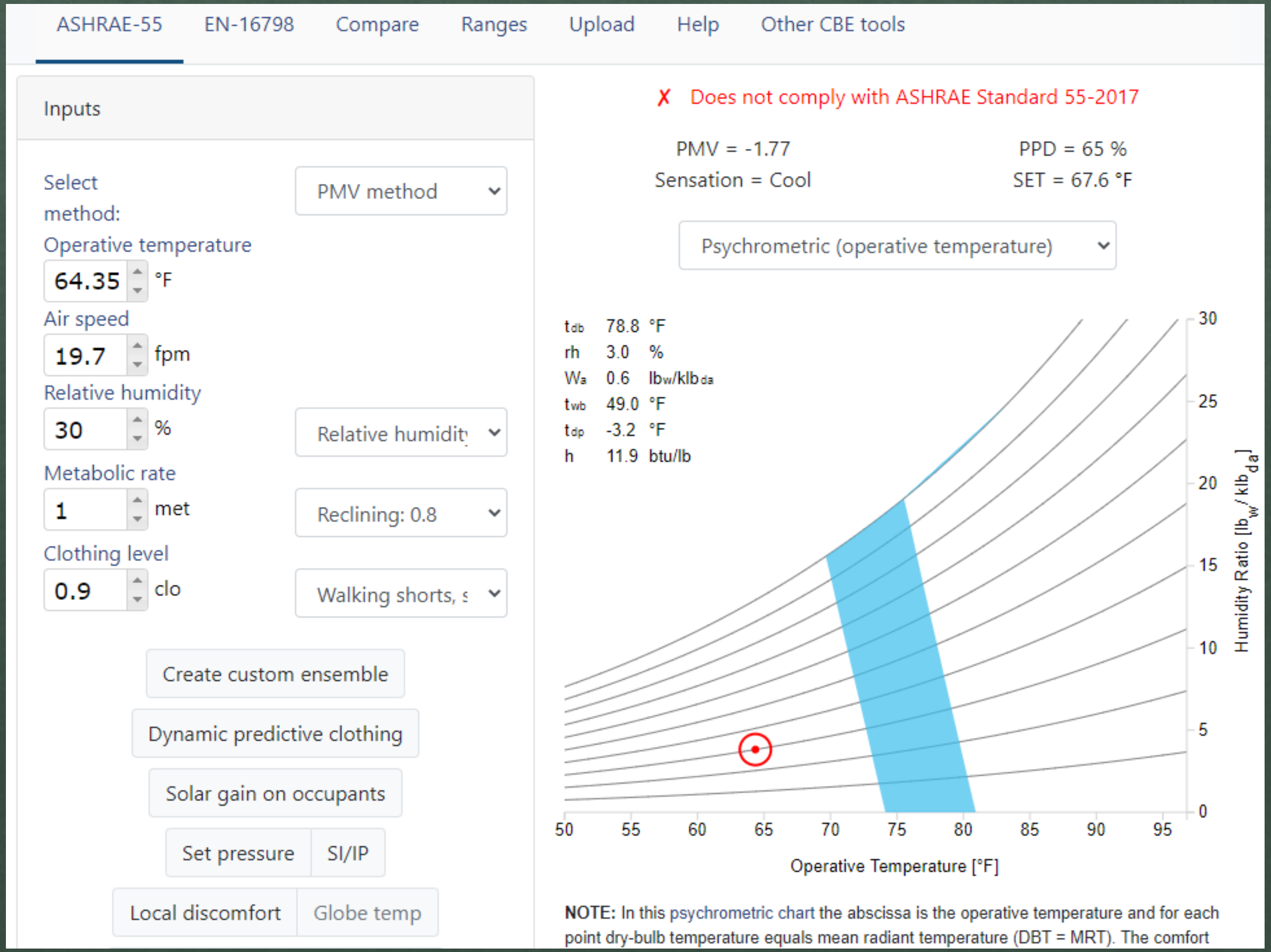
MRT = 0.30*60F + 0.15*66F + 0.40*66F + 0.15*55F = 62.55F

Example: Brian's house in winter (software method)

- Thermostat 66F
- RH 30%
- Clo = 0.90 (typ. winter)
- Met = 1.0 (seated, reading)

T_{op} = ½ dry bulb + ½ MRT
= ½ 66F + ½ 62.7F
= 64.35F

Enter into: https://comfort.cbe.berkeley.edu/



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Let's unpack this…

- 65% of people are predicted to find it uncomfortable
- Misses ASHRAE 55 by a long shot (you want to be in the blue zone)

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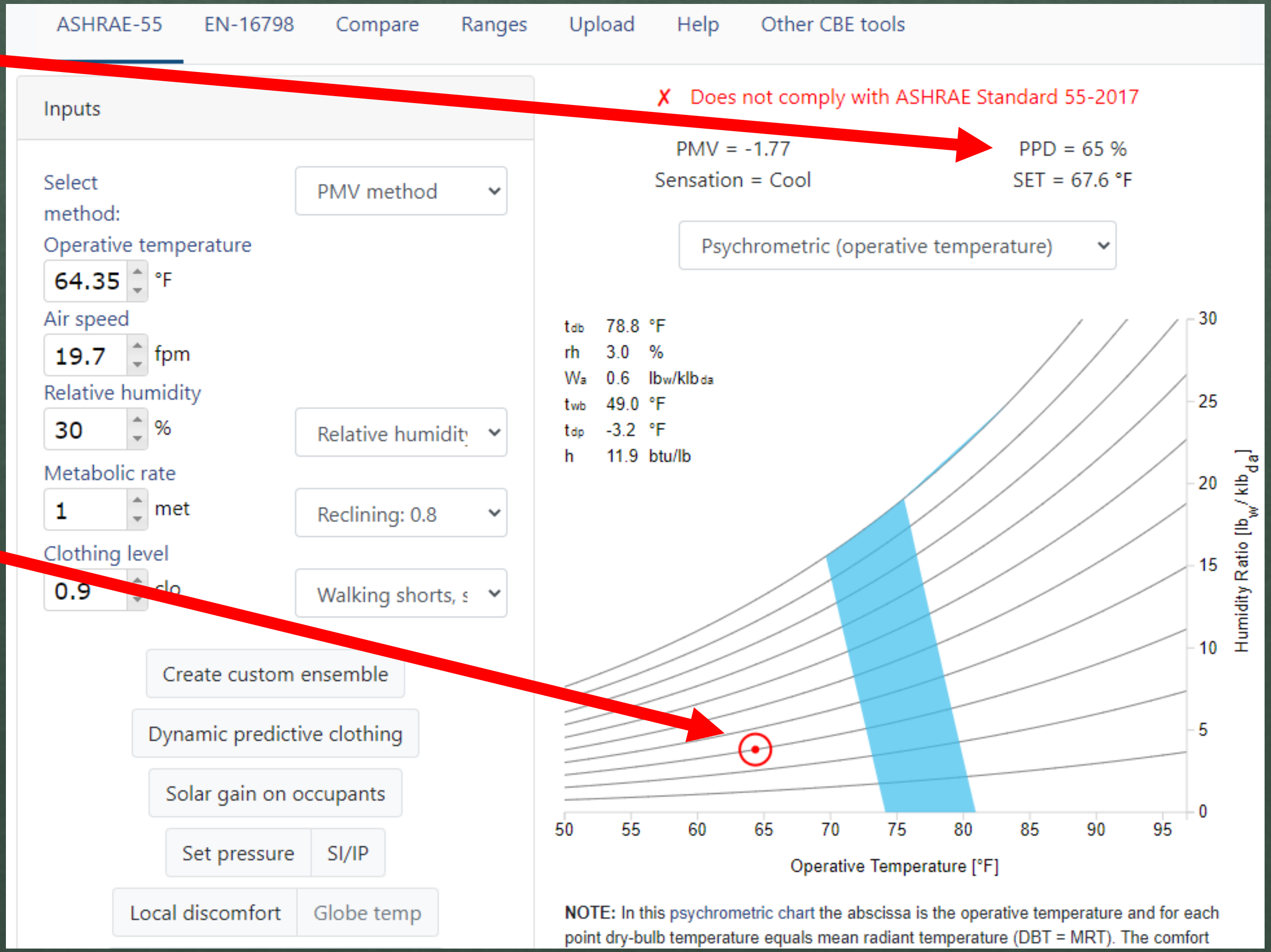


How do you fix it?

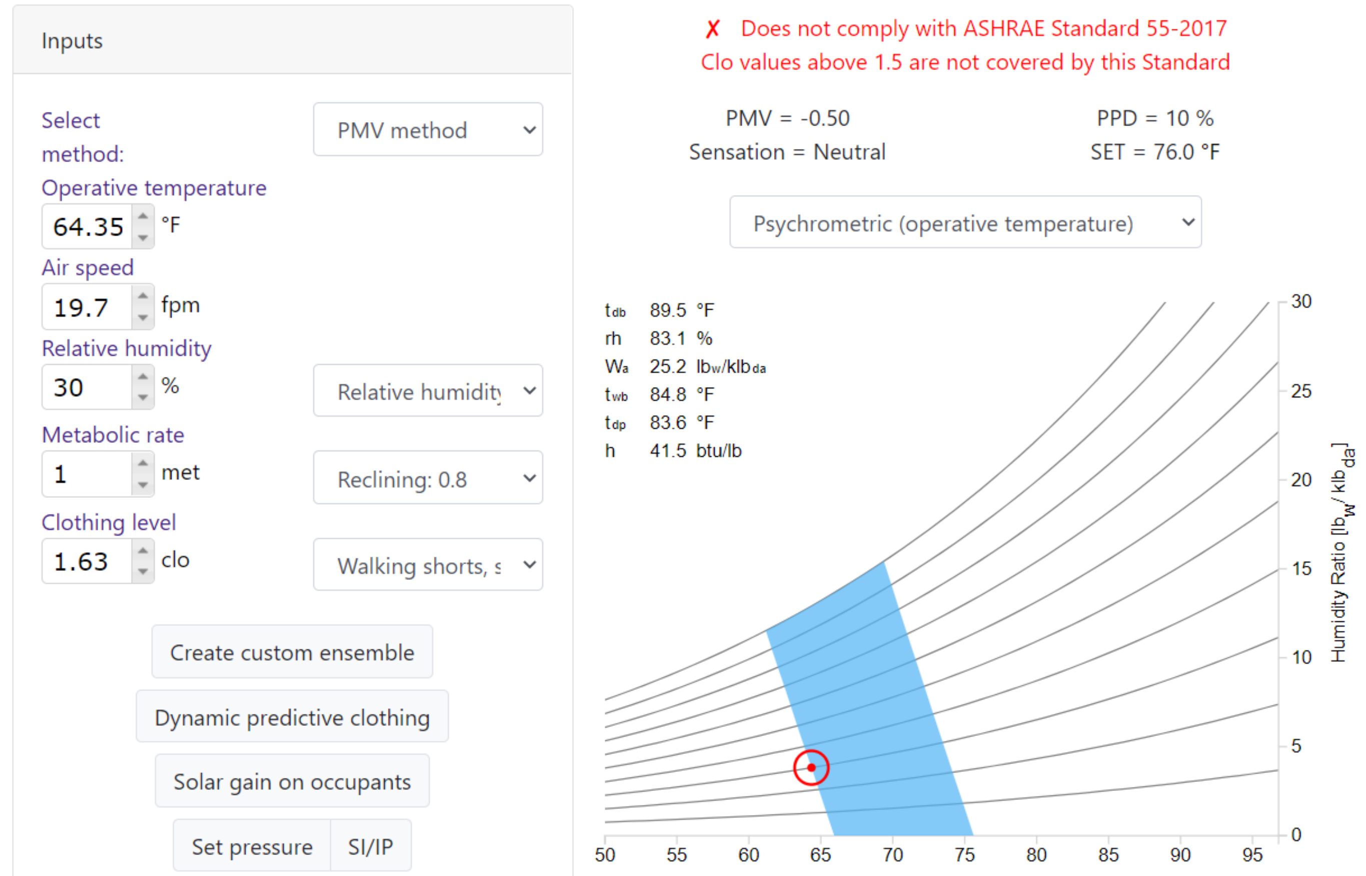
Tools:

- More clothing
- Higher metabolic rate
- Higher MRT (increase surface temperatures)
- Cranking the thermostat (but first let's not)

…via more clothes

All things equal, I need to reach Clo = 1.63 to get to "neutral" comfort

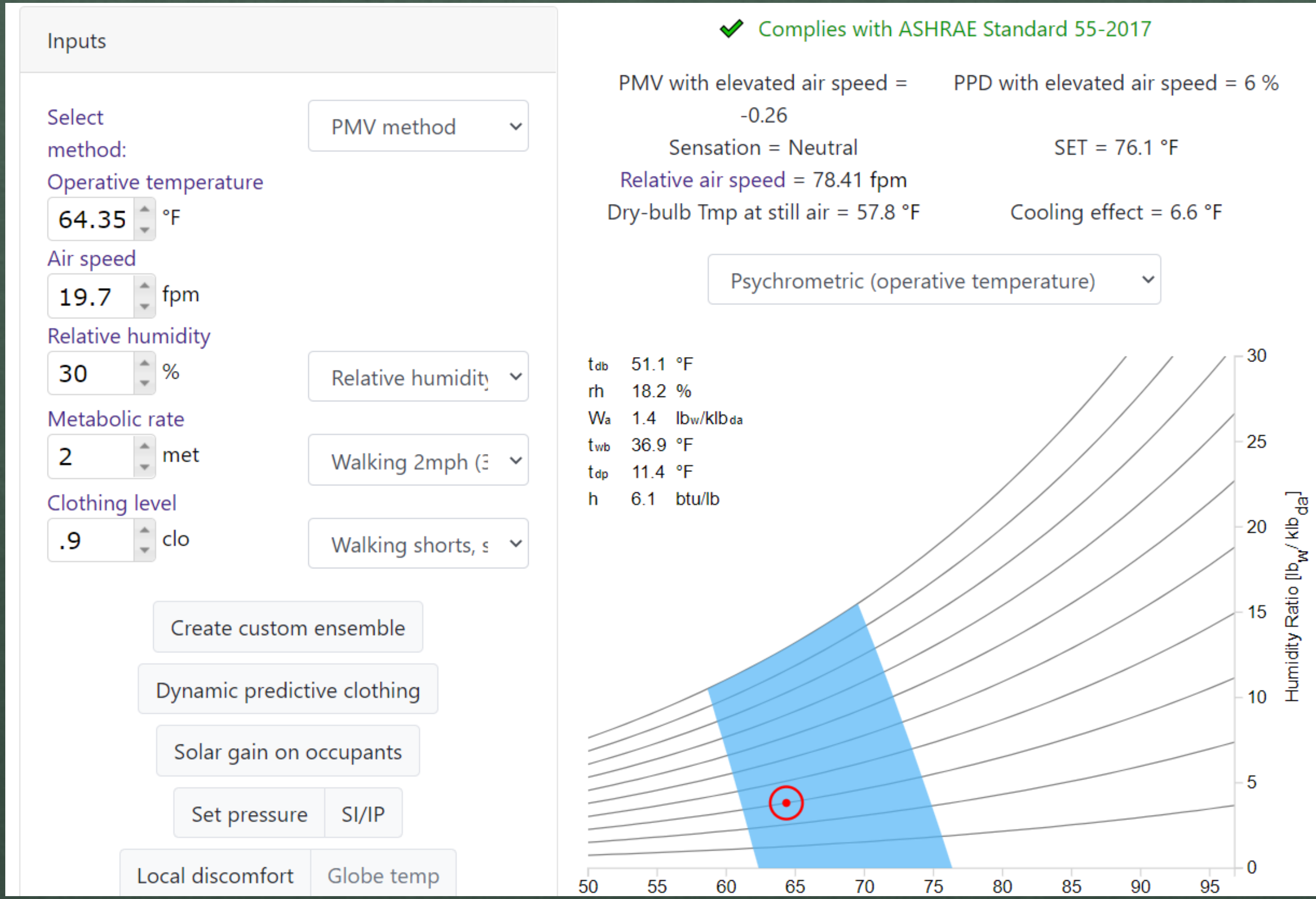
For example, adding 2 thick sweaters (adds 0.36 each to Clo)



…via higher metabolic rate

Jump to about 2.0 met value

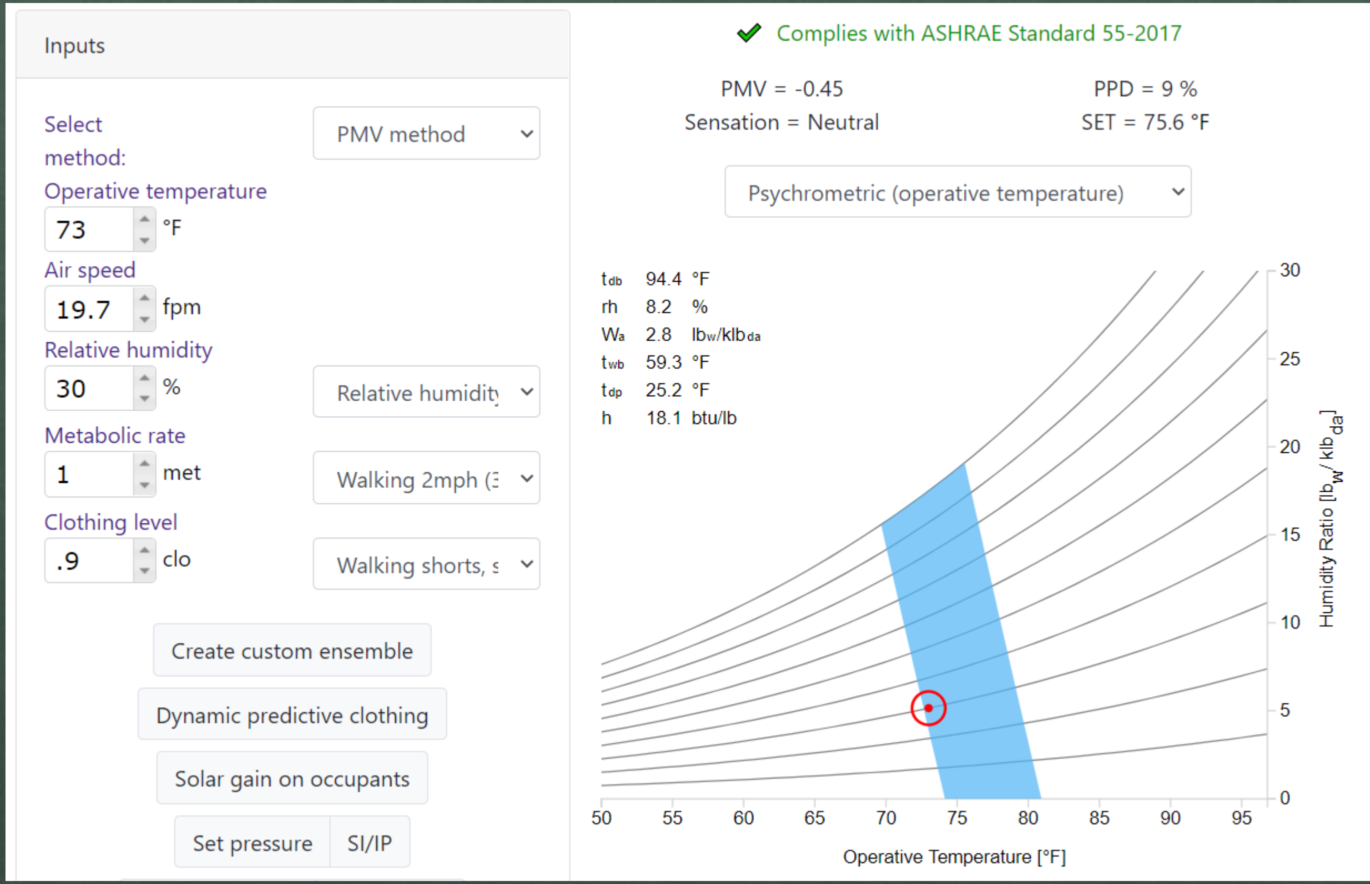
For example, walking at 2 mph (an activity like cooking gets you close but not quite)



…via higher MRT

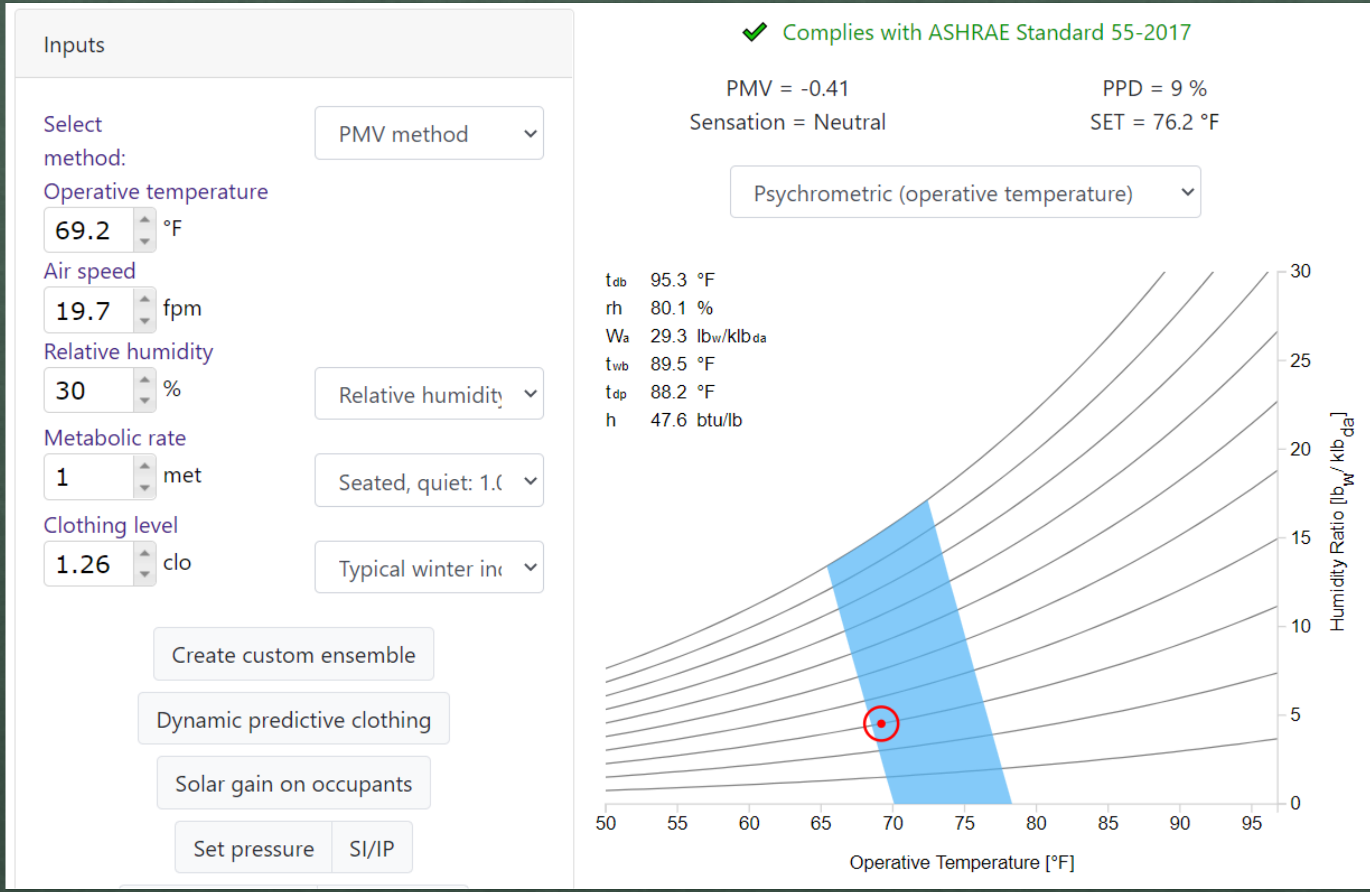
Increase T_{op} from 64.35F to 73F

- 90F radiant floor gets you to about MRT 72.5, T_{op} = 69.25 ➔ not enough
- 90F radiant floor plus room temp of 73.5F does it, however
- But really?



More realistic

- Thermostat 68F
  - With 85F radiant floor
  - MRT ~ 70.3F, T_{op} ~ 69.2F
- RH 30%
- Clo = 1.26 (winter indoors wear plus warm sweater)
- Met = 1.0 (seated, reading)



Remember to also consider

Radiant temperature asymmetry

- Ceiling ≥ 9F warmer than floor
- Ceiling ≥ 14F cooler than floor
- Wall ≥ 41F warmer than air
- Wall ≥ 18F cooler than air

Draft

- If clo < 0.7, met < 1.3, and T_{op} < 72.5F, keep < 30 fpm
- Upper limit is 240 fpm with right conditions

Vertical air temperature difference

- Head and ankle difference < 5.4F

Floor surface temperature

- Comfort range *while wearing shoes* is 66.2F – 84.2F

Cyclic variations, drifts, and ramps

- Operative temperature varies
  - Within 2F if cycling within a 15-minute period
  - Within 4F over 1-hour period

Tools beyond ASHRAE

Useful tools

1. Graphic comfort zone method (chart)
2. CBE Thermal Comfort tool, https://comfort.cbe.berkeley.edu/
3. THERM or other simulation software
4. Payette glazing tool
5. Cardinal tool
6. Free stuff! (for later)

Covered already

THERM

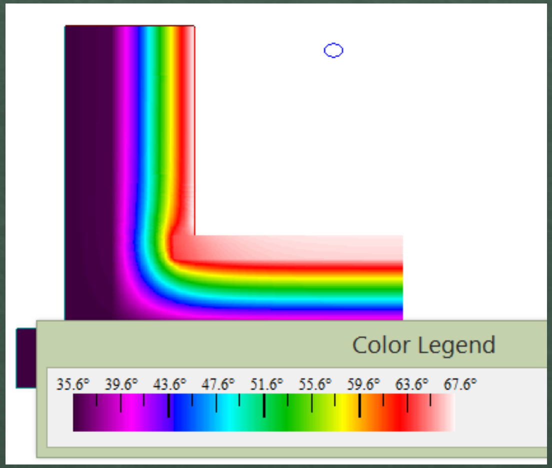
2D heat transfer modeling software

- Lawrence Berkeley National Laboratory
- Free, https://windows.lbl.gov/software/therm

Example: Residential slab insulation model…

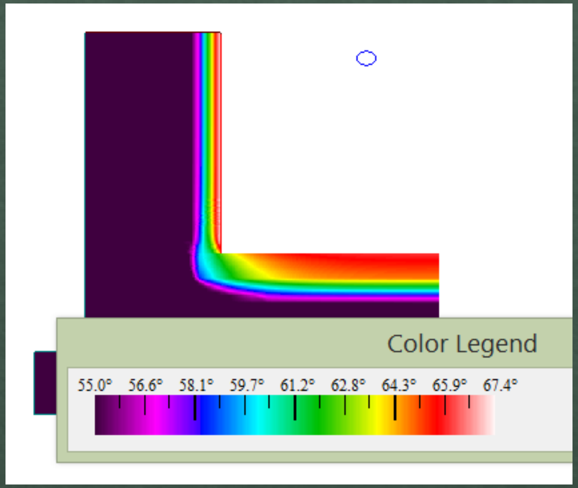
R-30

Slab 67F



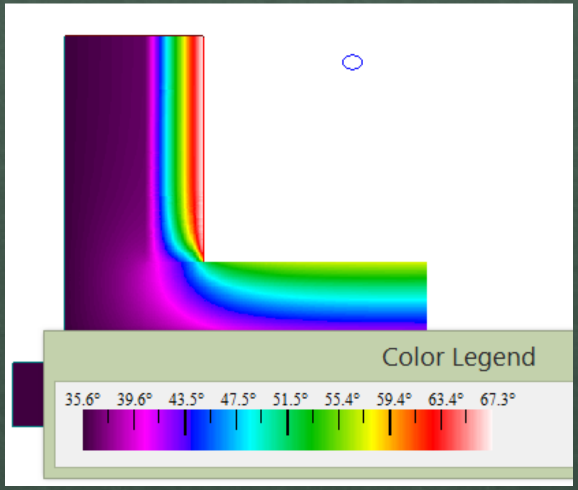
R-10

Slab 63-65F



R-1

Slab 52-57F



THERM model (compliments of Chris West) modified from:
4" slab, 12" EPS (R-50), 68F interior, 36F soil, 1.42 surface film coefficient

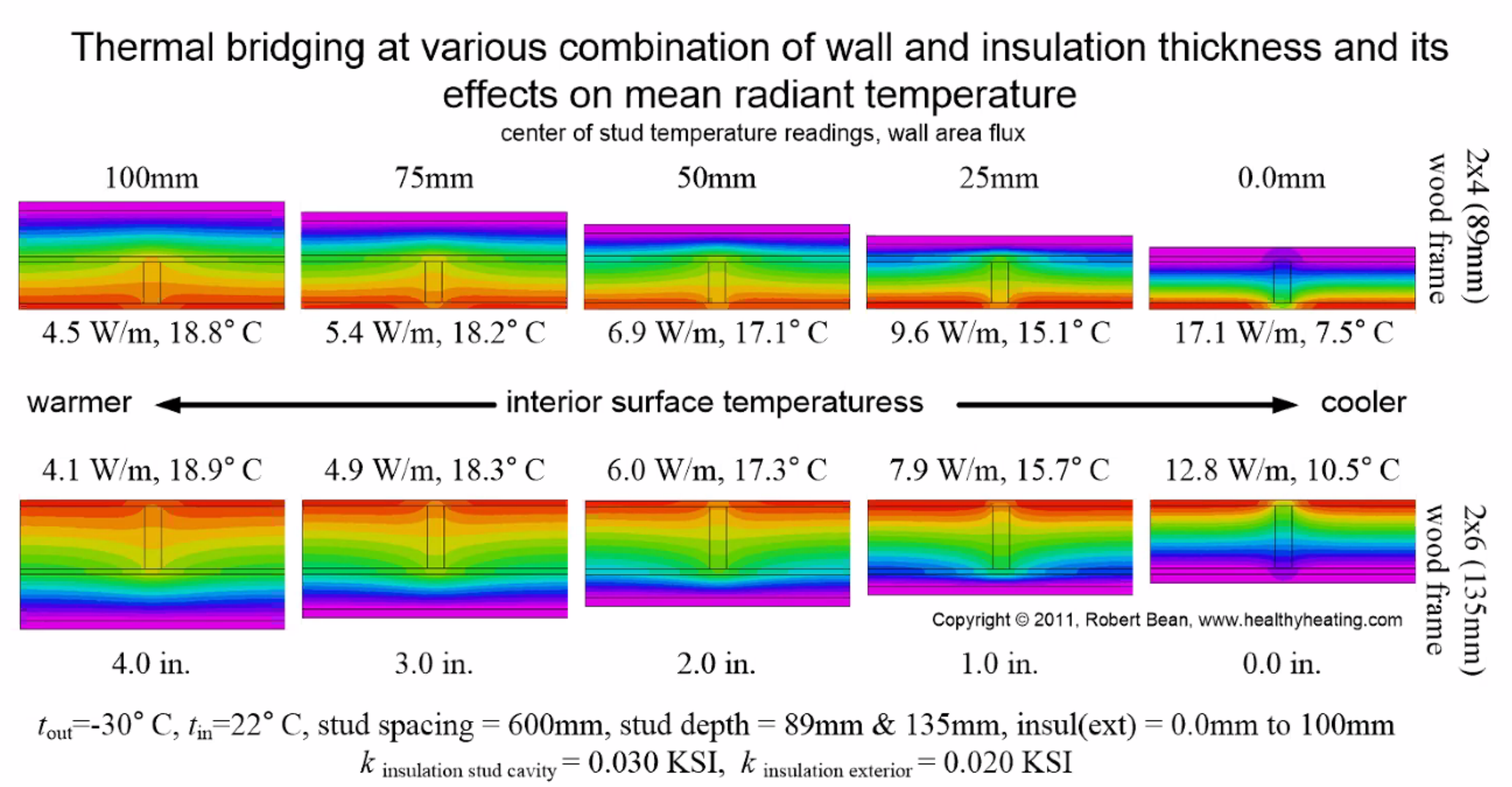
Recall…

- Local discomfort due to radiant temperature asymmetry when…
  - Ceiling ≥ 9F warmer than floor
- Floor surface temperature
  - Comfort range while wearing shoes is 66.2F – 84.2F

Yet many codes (e.g. Vermont) do not require under-slab insulation for unheated slabs

- Result: Slab temp in the 50s ➔ discomfort
- Think about MRT/comfort (and potential for summer condensation and associated problems)

Thermal bridging / continuous insulation effects on MRT



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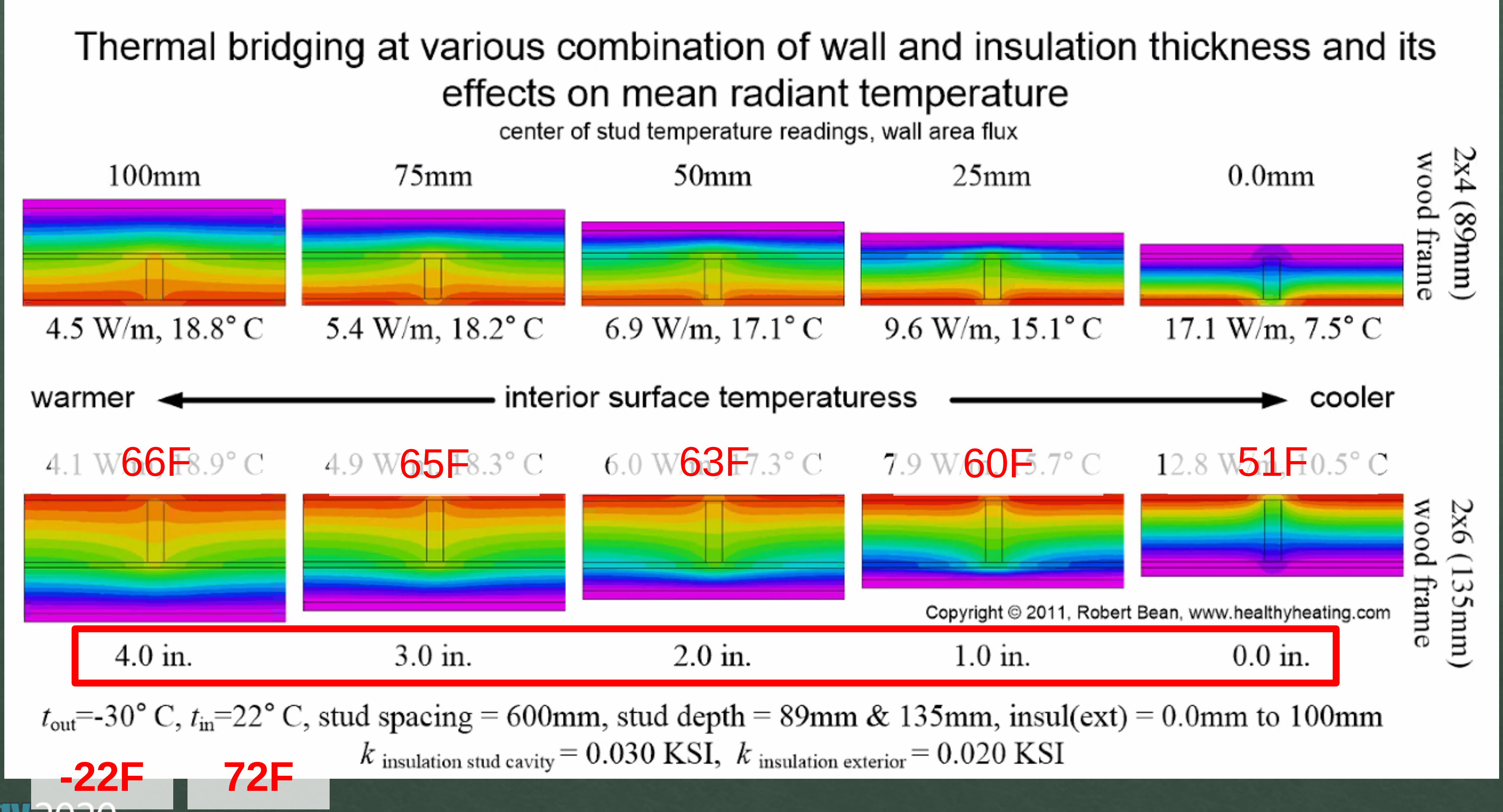
Courtesy Robert Bean http://www.healthyheating.com/

Thermal bridging / continuous insulation effects on MRT



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Courtesy Robert Bean http://www.healthyheating.com/

Payette glazing tool

https://www.payette.com/glazing-and-winter-comfort-tool/

The software models:

- Radiant discomfort
- Downdraft discomfort*

Payette note: Perimeter heat warms inner glass, which has the effect of *raising* effective u-factor (wrong way!)

* ASHRAE tools do not account for this

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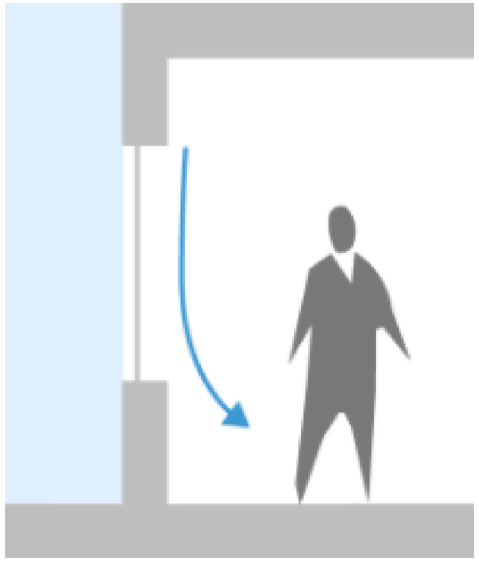
Understanding Discomfort

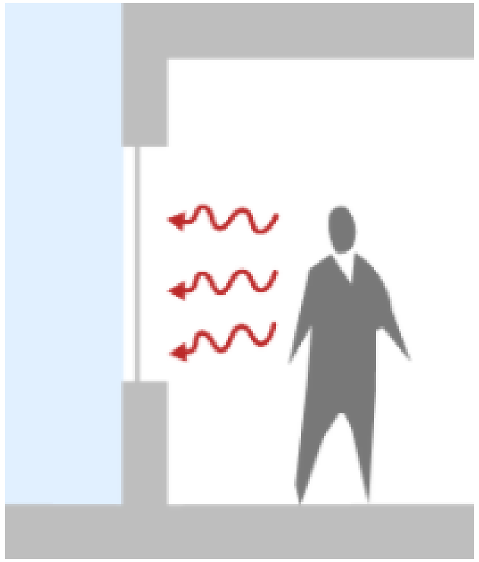


DOWNDRAFT DISCOMFORT

Cold convective air currents, formed by warm room air hitting the cold window surface, create discomfort at the occupant's feet and ankles. The strength of these currents depends on the height of the window pane, as well as the interior temperature of the glass.

To minimize downdraft discomfort, try:

– decreasing the window height
– decreasing the window U-Value
– using a glazing assembly without a room-side low-e coating



RADIANT DISCOMFORT

Cold interior glass surfaces affect the mean radiant temperature of occupants, and in turn make them feel cold. This discomfort depends on how much the occupant "sees" of the glass, how cold the interior glass surface is and the emissivity of the glass. If the glass has a room-side low-e coating the radiant discomfort will be
greatly reduced.

To minimize radiant discomfort, try:

– decreasing the total amount of glazing
– decreasing the window U-Value
– increasing the sill height
– using a glazing assembly with a room-side low-e coating

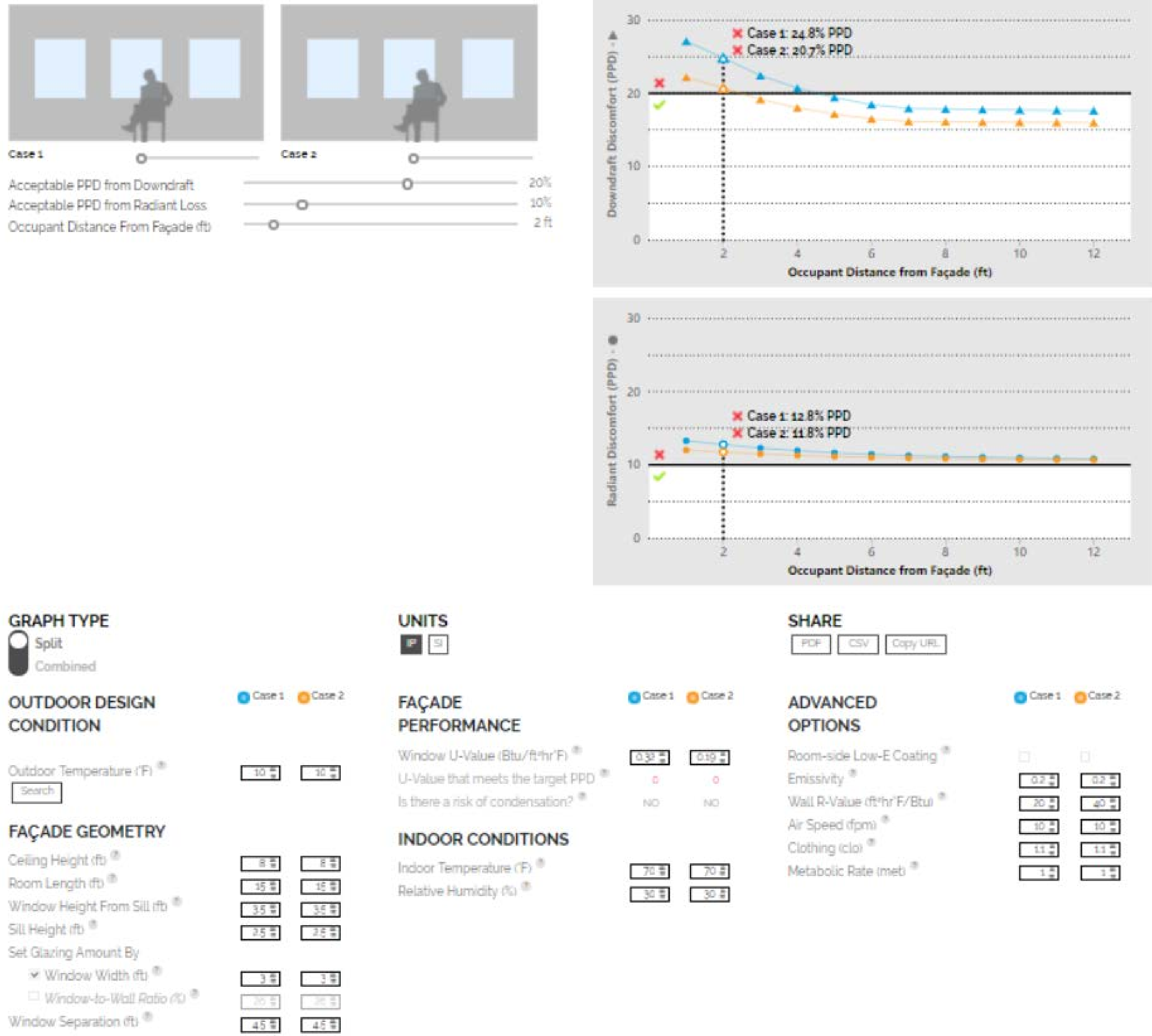
Payette glazing tool

https://www.payette.com/glazing-and-winter-comfort-tool/

Sample scenario

- Blue = code walls and windows
- Yellow = high performance walls, triple-glazed windows

Note: Does not take solar radiation into account – arguably, this can warm an occupant in winter (if orientation and time of day are aligned), but it's (probably) impossible to design a building to count on this (barring 360-degree windows or building rotation, and only occupied during daytime)



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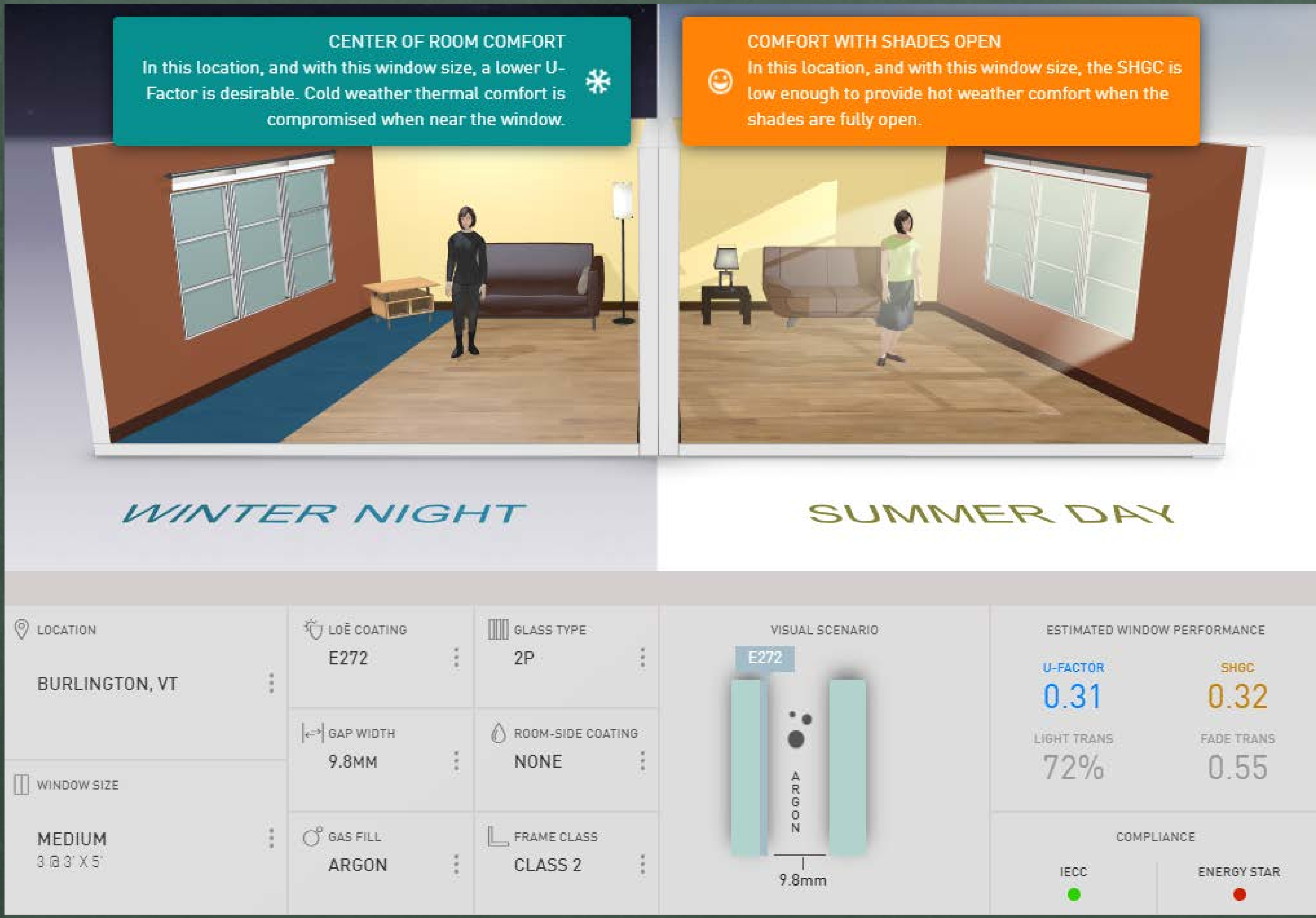
Cardinal glazing tool

https://www.cardinalcorp.com/technology/applications/comfort-calculator/

The software only accounts for glass (and it goes into the weeds)

In this scenario, a double pane window results in discomfort anywhere within 4-5' of a window on a winter night



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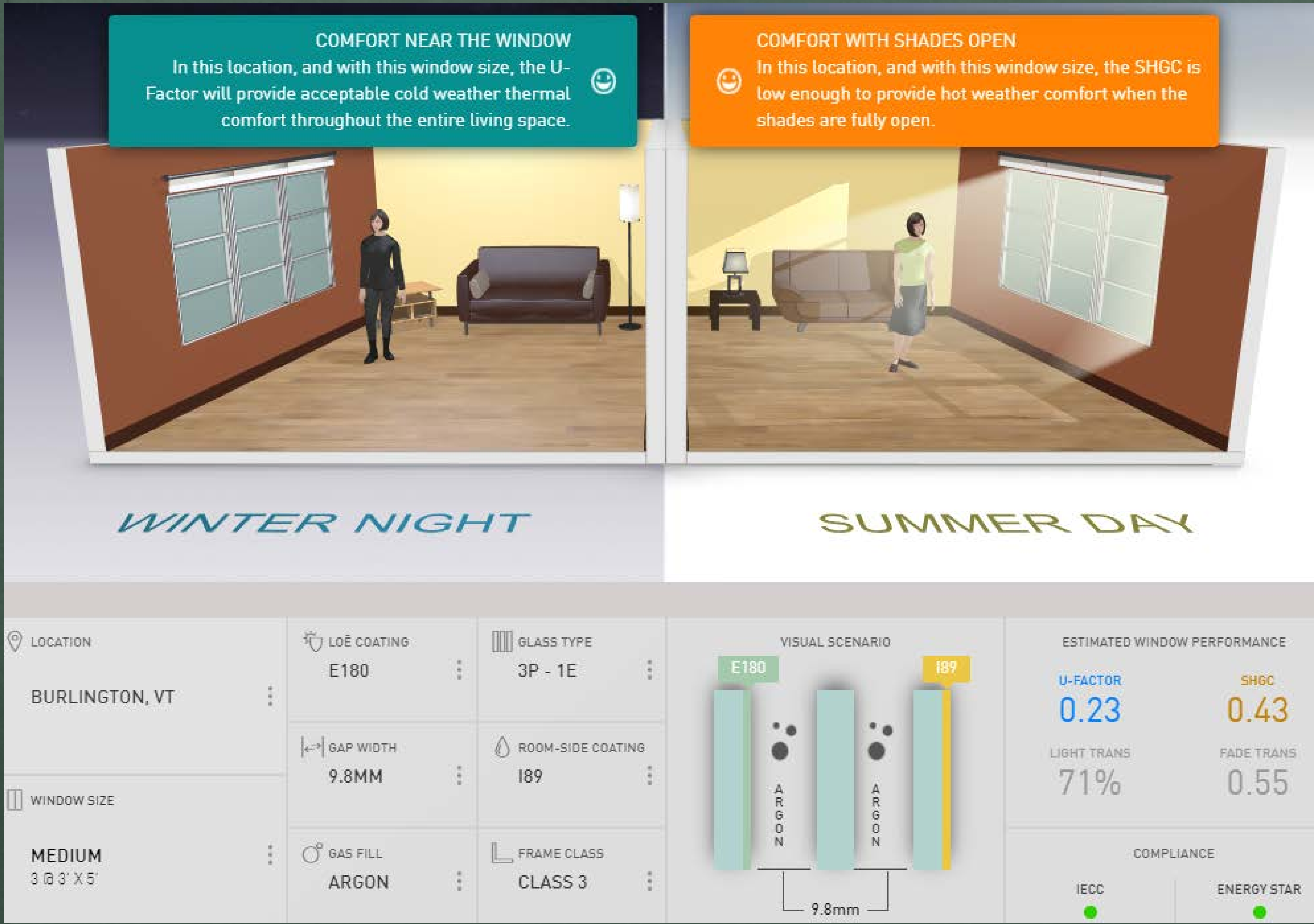
Cardinal glazing tool

https://www.cardinalcorp.com/technology/applications/comfort-calculator/

Tweak a little (in this case to a triple)

…and the blue band disappears



Designing for comfort

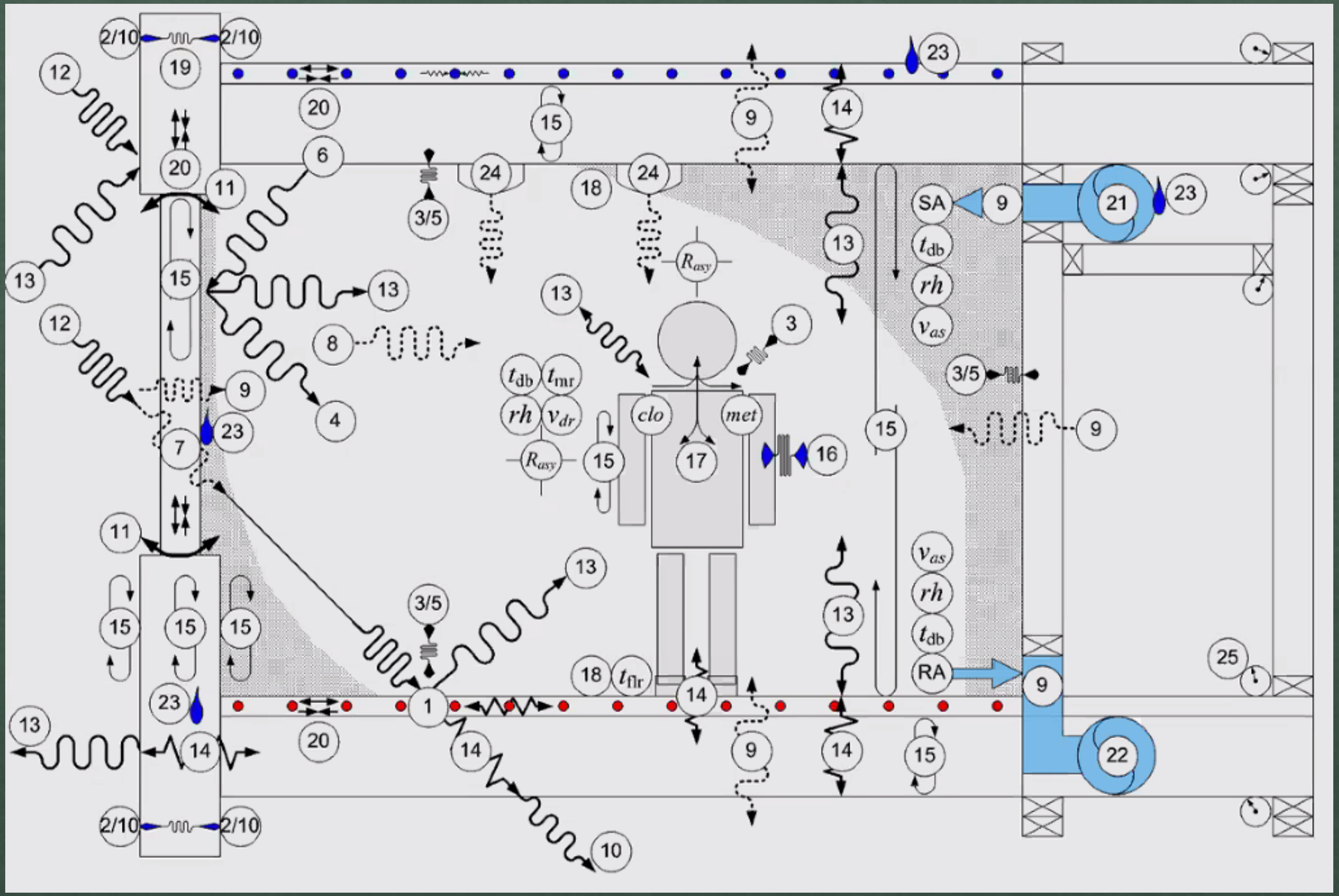
Remember…

There's a lot going on.

Codes ignore the effects of most of this.

The human body does not.

This would be easier to nail down if it weren't for the people.



Courtesy Robert Bean http://www.healthyheating.com/

Thermal comfort review

- Metabolic rate (met)
- Clothing insulation (clo)
- Radiant temperature
- Air temperature
- Air speed
- Humidity

Personal factors
you can't reliably influence

One-time opportunity (design)

Controls can help (but some
require design/infrastructure)

Steps (mine, not ASHRAE's)

1. Model. Use free tools to justify large surfaces being as well-insulated as reasonable.
    - Use ASHRAE numbers for metabolic rate and summer/winter clothing insulation
2. Check that the local discomfort guidelines are being met (these are ignored by the software).
3. If (1) or (2) are out of line, point out the comfort hit to client *which a higher thermostat setting may not totally fix*. Think of ways to improve this.

Costs of compensating?

Assume a moderate winter condition:

- 15’ x 20’ living room
- Person with typical winter clothing seated 2.5’ from a picture window
- 30% relative humidity
- 70F air temperature (10F outside)
- **Code-level** building shell, draft-free (aside from window effects)

How do we make this person comfortable?

Costs of compensating, cont.

As is:

✗ Does not comply with ASHRAE Standard 55-2017

PMV = -1.36 PPD = 43 %

Sensation = Slightly Cool SET = 70.0 °F

(and this is with an air temperature of 70F)

Costs of compensating, cont.

As is:

✗ Does not comply with ASHRAE Standard 55-2017

PMV = -1.67 PPD = 60 %

Sensation = Cool SET = 68.2 °F

(and this is with an air temperature of 70F)

To reach borderline comfort, options include:

Compensator*	Notes
Increase air temp to 82F	Radiant discomfort?
Add thick sweater and increase air temp to 73F	Must wear sweater?
Add a vest and heat floor to 90F	Floor/air discrepancy?

* With double-glazed u-0.28 windows, no matter the compensation strategy there may be downdraft discomfort for anyone within 4’ of the window

Costs of compensating, cont.

As is:

✗ Does not comply with ASHRAE Standard 55-2017	
PMV = -1.67	PPD = 60 %
Sensation = Cool	SET = 68.2 °F

(and this is with an air temperature of 70F)

Or: Add build a great thermal shell and add a long sleeve t-shirt

Costs of compensating?

Assume a moderate winter condition:

- 15’ x 20’ living room
- Person with typical winter clothing seated 2.5’ from a picture window
- 30% relative humidity
- 70F air temperature (10F outside)
- **Code-level** building shell, draft-free (aside from window effects)

How do we make this person comfortable?

Grade: D
“The worst you can legally build to”

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My takeaways

- Aim higher than code-level windows
  - Double-pane / ENERGY STAR windows can still cause downdraft discomfort and strongly contribute to radiant discomfort (in addition to condensation and frost)
  - VEIC's old office on a 15F day: 55F glass, 44F frame edges
- Don't put a cold floor or a ground-connected heat sink under your feet
  - Many codes do not require sub-slab insulation for unheated slabs
- Insulate your walls and ceilings
  - Bonus: This goes a long way towards eliminating the pesky local discomfort items

Choose one

Design for comfort

(this does <u>not</u> mean code minimums)

OR

Set client expectation that 2 or more of the following might be needed to achieve comfort in their dream home:*

- Additional clothing (e.g. shoes, multiple sweaters)
- Very-warm radiant floor
- Woodstove on
- Avoid sitting near windows
- 75F-plus setpoint

*Disclaimer:
These will vary by home/building, but *can* be evaluated with relative ease… Based on ASHRAE 55 simulation

Beyond ASHRAE

1: IEQ

IEQ = Indoor Environmental Quality

IEQ = IAQ +ITQ + ILQ + ISQ + IOQ + IVQ

where **I** = Indoor, **Q** = Quality

and

A = Air
T = Thermal
L = Lighting
S = Sound
O = Odor
V = Vibrations

Much more to comfort than just thermal!

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Ref: *Definition of Indoor Environmental Quality (IEQ),* Healthy Heating, http://www.healthyheating.com/Defintion_of_indoor_environmental_quality.htm#.WrEB7WobOUv

1: IEQ

IEQ = Indoor Envi

Ventilation, ability to operate windows, healthy materials

Insulation, air sealing, windows, well-designed heating and cooling

IEQ = IAQ +ITQ + ILQ + ISQ +

Windows, lighting bulb/fixture design

where **I** = Indoor, **Q** = Quality

and
A = Air
T = Thermal
L = Lighting
S = Sound
O = Odor
V = Vibrations

Insulation, windows, orientation

Ventilation, air sealing (between MF units), healthy materials

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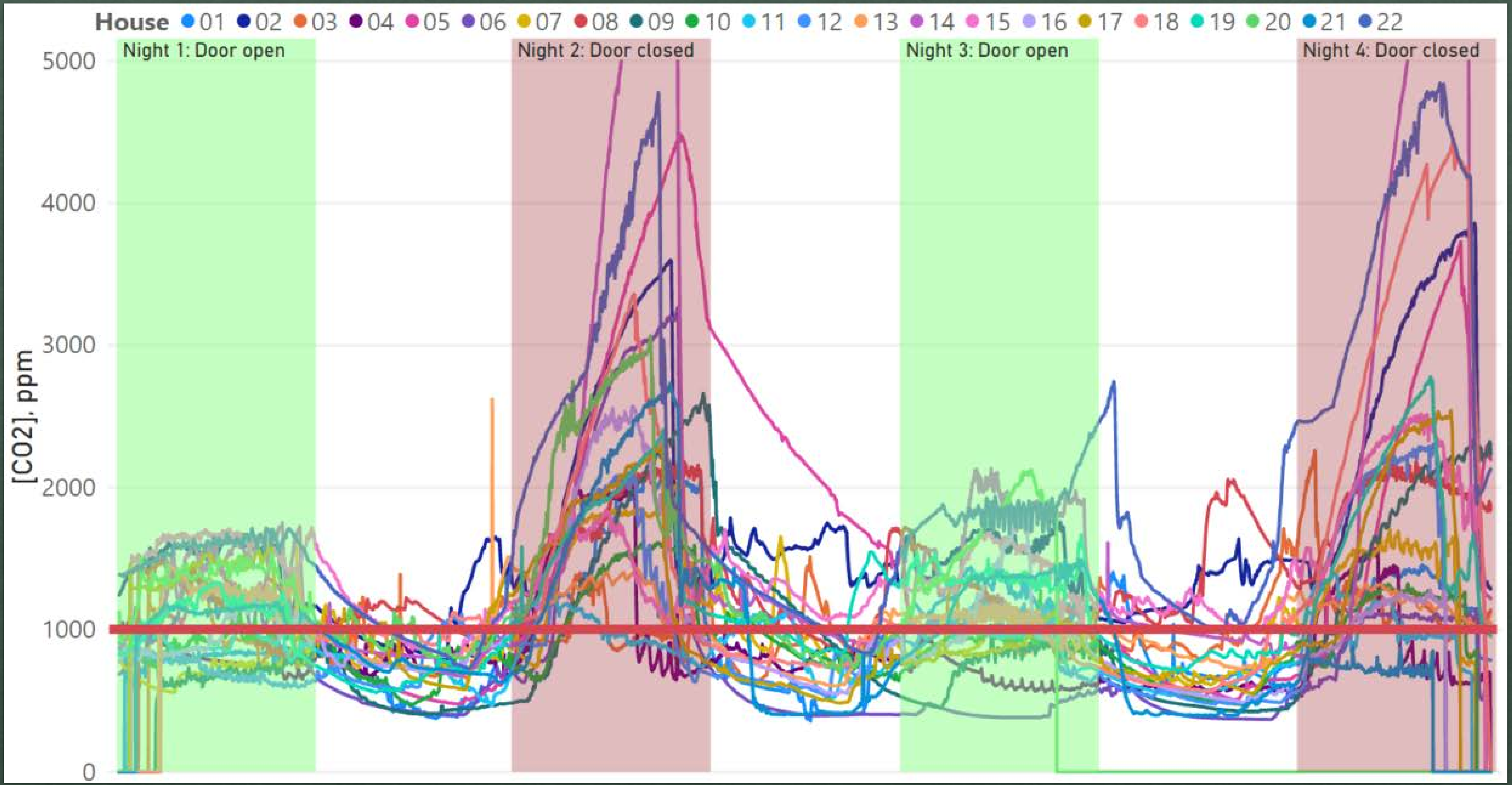
Ref: *Definition of Indoor Environmental Quality (IEQ),* Healthy Heating, http://www.healthyheating.com/Defintion_of_indoor_environmental_quality.htm#.WrEB7WobOUv

1. IAQ tangent: Ventilate, right



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Ref: Breathe Well, Sleep Well: Cold-Climate Ventilation,
https://www.efficiencyvermont.com/news-blog/whitepapers/breathe-well-sleep-well-improving-ventilation-in-cold-climate-homes

2: My floor feels cold!

Contact coefficient ($kCal/Cm^2hr^{0.5}$) ➔

The higher the contact coefficient, the better the material is at *drawing heat out of the feet*

- Concrete 25
- Linoleum 9
- Oak 7
- Pine 4
- Cork 2

Ref: *Floor Coverings: thermal and thermo-optical properties*, Healthy Heating, http://www.healthyheating.com/Radiant_Design_Guide/Floor-covering-R-values.htm#.Wm8gCq5KuUs

3: Adaptive comfort

1. *Behavioral adaptation*, or **control**
   - Putting occupant in the "driver's seat" can expand comfort zone
   - Conscious and unconscious actions that we take to adjust our thermal environment
2. *Physiological adaptation*, or **acclimatization**
   - Biological changes caused by long-term exposure to conditions
3. *Psychological adaptation*, or **expecting/getting used to it**
   - Perception/reaction to conditions due to past experience or present/future expectations
   - E.g. cool weather *outside* can lead to people being comfortable at a slightly lower range of temperatures *inside*
   - James Wise: "anytime you can get anyone in engineering to pay attention to anything that comes out of psychology, it's a major victory"

Ref: *Boost Happiness and Save Energy with Adaptive Thermal Comfort*, BuildingGreen,
https://www.buildinggreen.com/feature/boost-happiness-and-save-energy-adaptive-thermal-comfort

3: Adaptive comfort → Impacts

We seasonally shift our comfort range

- Wearing shorts on the first 50 degree day of spring vs. first week of November
- 85F feels great outdoors (with shade and a breeze), but usually terrible in a sealed building

“Thermal boredom” (dislike of unchanging conditions) is real

- Donald McIntyre: “It can be argued that achieving a steady optimum temperature is akin to finding the most popular meal at the canteen and then serving it every day.”

3: Adaptive comfort → Impacts

Control over conditions expands individual comfort zones

- Give the 20% (ASHRAE 55) of people who are uncomfortable the ability to fine tune their situation

Naturally ventilated spaces (where air is supplied/removed without mechanical systems) can **expand comfort zones** (and ASHRAE 55 recognizes it)

- Research by Gail Brager and Richard de Dear found that occupants of mechanically ventilated buildings were twice as sensitive to temperature changes as those in naturally ventilated buildings
- “Such a finding suggests that people in air-conditioned buildings have higher expectations for thermal consistency,” they explain, “and quickly become critical if thermal conditions diverge from these expectations.” In other words, we can become addicted to air conditioning.

Ref: *Boost Happiness and Save Energy with Adaptive Thermal Comfort*, BuildingGreen, https://www.buildinggreen.com/feature/boost-happiness-and-save-energy-adaptive-thermal-comfort

4: Hedonic response

- “Thermal delight”
- Relies on contrasts
- Example:
  - On a cold day, it feels great to enter an overly warm building
  - As you adjust, it might feel *too* warm after 10 minutes

Ref: *So Sweet / And So Cold: Sensation, Perception, and Hedonic Response*, Terrapin Bright Green, 2018, https://www.terrapinbrightgreen.com/blog/2018/01/5008

4: Hedonic response

- No: Uniformity
  - Stable temperature
  - Brute-force, sealed environment
  - “Acceptability” for 80% of people (ASHRAE 55)
- Yes: Variety, Sovereignty
  - Temperatures float in line with natural swings
  - Exploiting air motion
  - Individual control
  - Surface choices (e.g. soft leather on walls, cool terracotta tiles underfoot, the feel of wood grain on your hands)

} Thermal landscaping

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Ref: *So Sweet / And So Cold: Sensation, Perception, and Hedonic Response*, Terrapin Bright Green, 2018, https://www.terrapinbrightgreen.com/blog/2018/01/5008

5: Room to room variation

- ASHRAE 55 says nothing
- ACCA* Manual J:
  - 2F ideal
  - 4F allowable

*Air Conditioning Contractors of America

6: More on windows

Source: *Window Performance for Human Thermal Comfort*

- Highlights from approx. 200 papers and studies
- Developed “Window Comfort Rating” equation for winter

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Ref: *Window Performance for Human Thermal Comfort: Final Report to the National Fenestration Rating Council*, Center for the Built Environment & ARUP, Feb 2006, http://www.cbe.berkeley.edu/research/pdf_files/SR_NFRC2006_FinalReport.pdf

6: More on windows

These results indicate that even low-e double pane windows are **only good to about 20F**

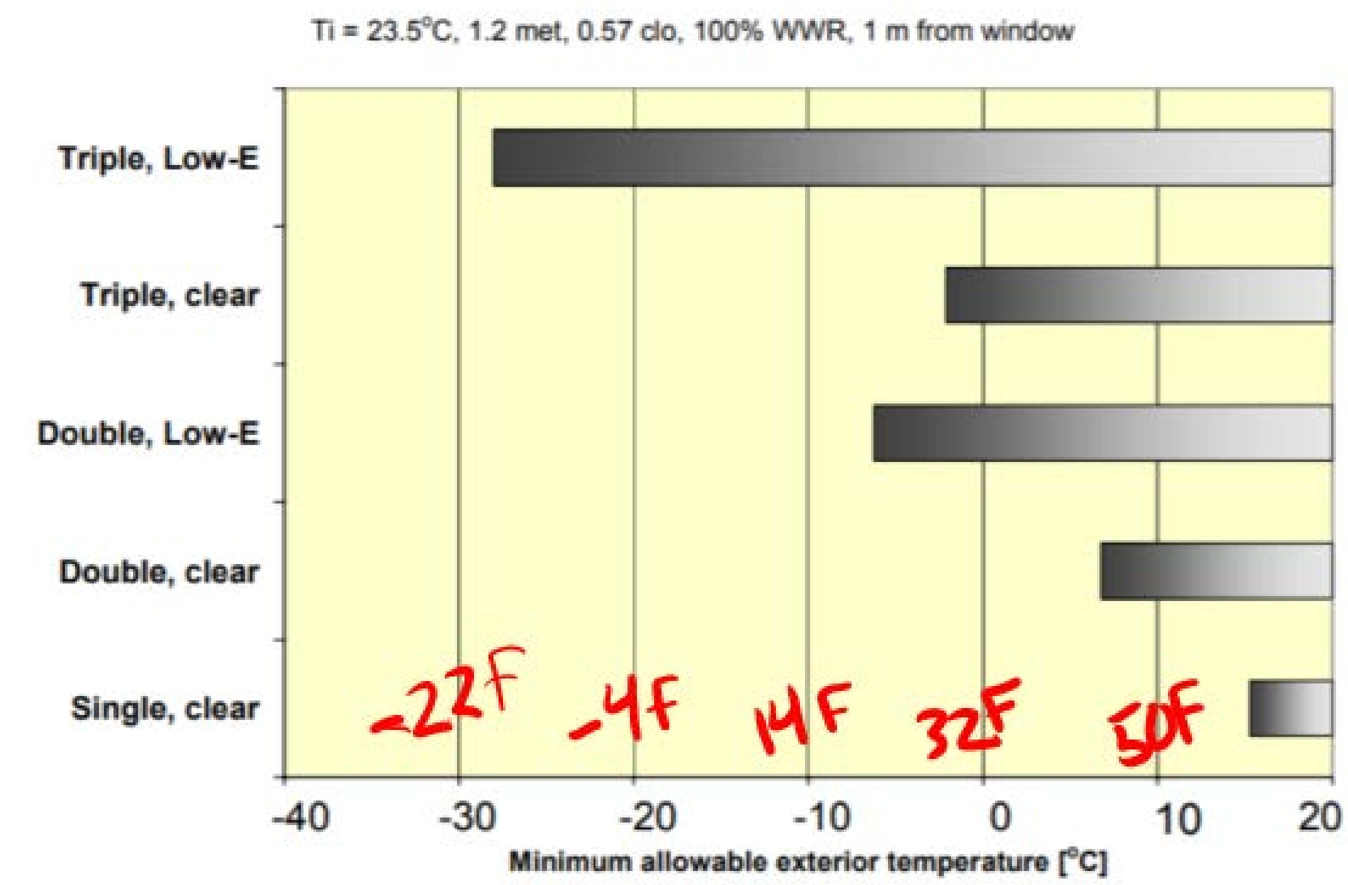

Figure 1: Winter window comfort rating – Minimum allowable exterior temperature

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Ref: *Window Performance for Human Thermal Comfort: Final Report to the National Fenestration Rating Council*, Center for the Built Environment & ARUP, Feb 2006, http://www.cbe.berkeley.edu/research/pdf_files/SR_NFRC2006_FinalReport.pdf

7: Less analytical, more human

- Victor Olgyay, 1963
- Design with Climate: A Bioclimatic Approach to Architectural Regionalism

Olgyay's Model

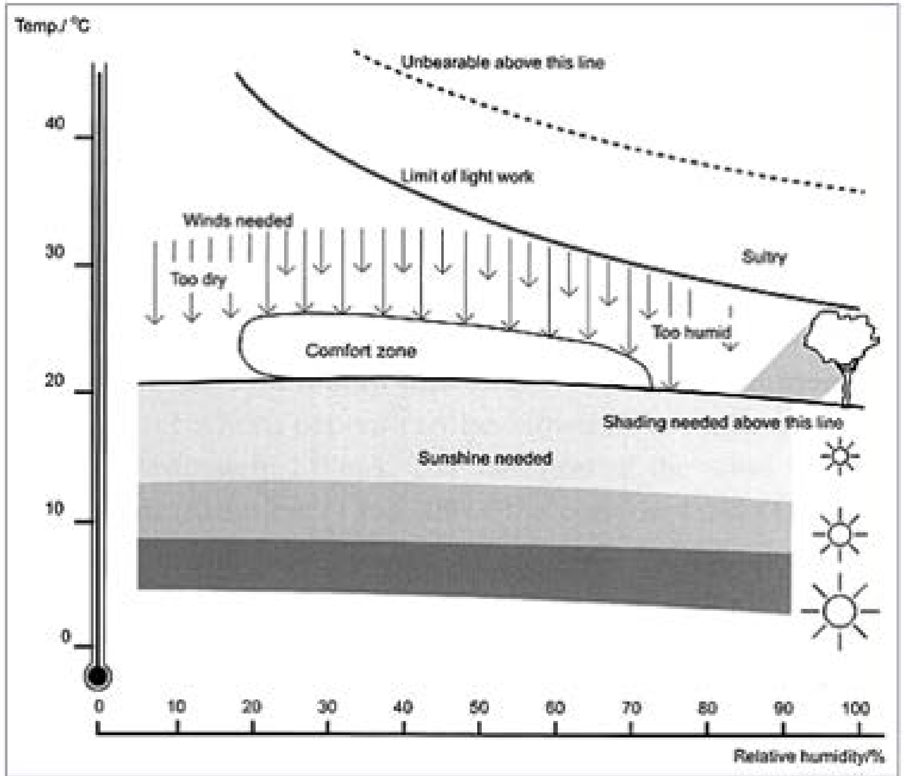

Figure 3. Simplified version of Olgyay's bioclimatic chart of thermal comfort zones.

From Stay Cool: A Design Guide for the Built Environment in Hot Climates by Holger Koch-Nielsen (James

Pulling it all together

Thermal comfort review

- Metabolic rate (met)
- Clothing insulation (clo)
- Radiant temperature
- Air temperature
- Air speed
- Humidity

Personal factors
you can't reliably influence

One-time opportunity (design)

Controls can help (but some
require design/infrastructure)

Which one(s) are *typically* directly controlled in your home?
Which can be easily tweaked *after* something's built?

Code, plus one program's approach…

Requirement	Energy code*	EVT Base	EVT High Performance
Wall insulation (AG and band)	R-20 cavity	**R-26** Min R-5 continuous**	**R-40**
Under slab insulation	R-15 heated R-0 unheated	R-15 heated R-0 unheated	**R-30 heated or on grade R-20 unheated or below grade**
Insulation installation	No req't	Grade I	Grade I
Windows, u-factor	0.28 max	0.28 max	**0.21 max**
Air leakage, max	3.0 ACH50	2.0 ACH50	1.0 ACH50
Ventilation	EOV allowed	**High-efficiency balanced ventilation**	**High-efficiency balanced ventilation**

* Vermont 2020 Residential Building Energy Code, Package 4
** Subject to moisture safety guidelines

My take on all of this

Design:

- AGW continuous insulation, 2" min.
- Triple-pane windows
- Airtight, 1.0 ACH50 max
- Floor / slab insulation
- 24/7 high efficiency ventilation (don't blow cold air), quiet design (don't be loud), MERV 13 filtration

And sell its IEQ:*

- **Thermal comfort**
- **Quietness**
- **Fresh air-ness**
- **Natural light (without downdraft or radiant discomfort)**
- **Sense of wellbeing**

*Note the absence of "low energy bills" on this list

Listen to both sides

Thinking	Feeling
• Continuous insulation in walls • Invest in great windows • Air seal really well • Insulate all slabs • Ventilate with intent • Choose floor material wisely	• Give control (zones, windows, etc.) • Give variety* and let occupant adjust via clothing, activity • Choose materials with intent

*E.g. make temperature swings (seasonal, time of day) okay / purposeful

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Disclaimer

- This presentation is not intended to be a comprehensive program covering all aspects of this topic.
- All are participants are encouraged to read and follow applicable standards, codes and regulations related to this topic.
- The views and opinions following are the presenter's opinions and not necessarily the official position of the Maine IAQ Council, IAQnet LLC, or Healthy Indoors.

More on windows and solar radiation

Notes from: *Window Performance for Human Thermal Comfort: Final Report to the National Fenestration Rating Council*, Center for the Built Environment & ARUP, Feb 2006, https://escholarship.org/uc/item/6rp85170

- "With respect to solar radiation, we considered only diffuse radiation based on notion that direct sun falling on the body will cause discomfort in all but the coolest environments and that some action will be taken by the occupant to mitigate direct sun. Diffuse solar still has a significant effect on comfort, though significantly less than direct solar"
- "Absorbed radiation influences the temperature of the glass; the inside surface of heat absorbing glass can routinely reach temperatures above 120°F (50°C) in summer conditions, raising MRT by as much as 15°F (8°C). Transmitted radiation often causes discomfort if it falls directly on the occupant. A person sitting near a window in direct solar radiation can experience heat gain equivalent to a 20°F (11°C) (Arens et al. 1986) rise in mean radiant temperature. These radiant heating and cooling effects act on the occupant's body asymmetrically, causing some parts of the body to be considerably cooler or warmer than a uniform model like MRT can describe. Models need to consider the effect on local skin temperature in order to be sensitive to discomfort caused by windows."

More on windows and solar radiation, cont.

A window influences thermal comfort in three ways (Figure 2):

- long-wave radiation from the warm or cold interior glass surface
- transmitted solar radiation
- induced air motion (convective drafts) caused by a difference between the glass surface temperature and the adjacent air temperature

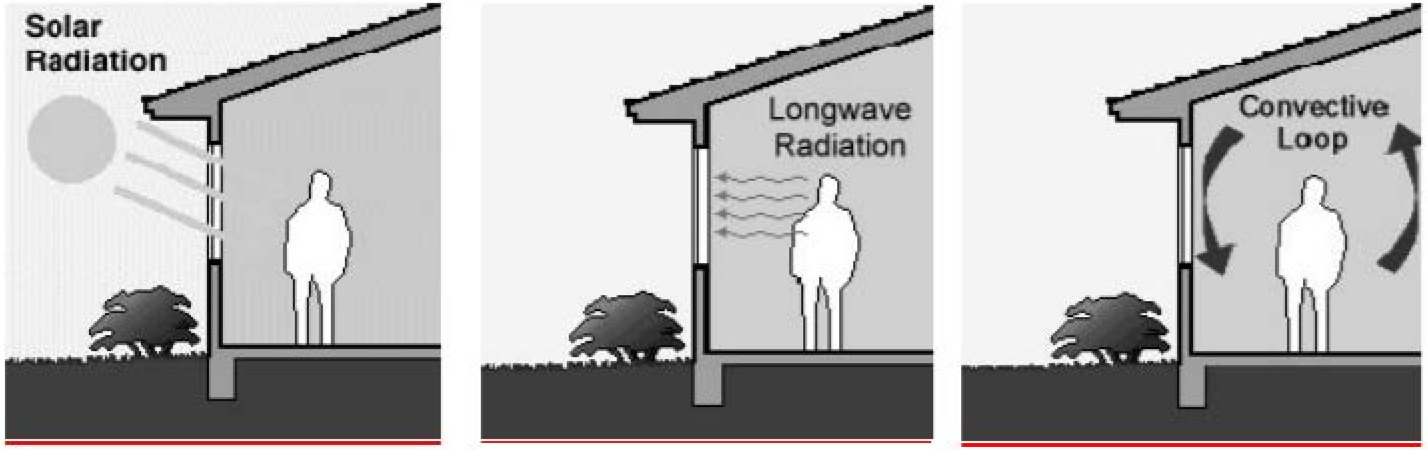

Figure 2: Window impacts on thermal comfort: solar radiation, long-wave radiation, convective drafts