Towards
21st Century thermal comfort standards?
Back to the basics

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SSPC55

Atlanta, GA - June 27, 2015

Intro - > Summary

- Why buildings do not perform according to design
  - Dynamic, not static
  - Interconnections/interactions (see ASHRAE Guideline 10)
- Fundamental data used for Standards 55 and (compliance with) as well as DCV design for 62 -- mostly from very old, out-of-date sources (e.g., wrong)
- ASHRAE Handbook revisions are typically only partial updates based on who volunteers to contribute.
- Human body size and, therefore, metabolic rates differ greatly from those of 1950s and 1960s when the met rates were developed.
- Very little is known about time constants to go from higher met rate (when entering a space) to the met rate for the space's usual activities.
- Transients may be more important than staying within a range.

Building Anatomies

Complex, interconnected, systems

- Building envelope
- HVAC system
- Occupants / activities
- Materials
- Furnishings / clutter
- Plumbing
- Cleaning and maintenance
- Microbial communities
- Health / well being
- Remediation

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The body as a system with a central control and many sub-system controls, valves, a 4-chamber and a 2 chamber pump, a distribution system, skin, outdoor air intake, exhaust, heating and cooling systems, etc..

The hypothalamus controls various physiological processes to *regulate* body *temperature*. Its control behavior is primarily proportional to deviations from set point temperatures with some integral and derivative response aspects. The most important and often used physiological process is regulating blood flow to the skin: when internal temperatures rise above a set point, more blood is directed to the skin.

This **vasodilation** of skin blood vessels can increase skin blood flow by 15 times [from 1.7 mL/(s · m^2)) at resting comfort to 25 mL/(s · m^2)] in extreme heat to carry internal heat to the skin for transfer to the environment.

When body temperatures fall below the *set point*, skin blood flow is reduced (**vasoconstricted**) to conserve heat. The effect of maximum vasoconstriction is equivalent to the insulating effect of a heavy sweater. At temperatures less than the set point, muscle tension increases to generate additional heat; where muscle groups are opposed, this may increase to visible shivering, which can increase resting heat production to 4.5 met.

Comfort envelope

- The comfort envelope in Figure 5.2.1.1 the standard is based on met rates of 1.0 to 1.3.
- In fact, in most indoor situations, unless people are actually sleeping, the actual met rates are in the range of 1.3 to 3.0

Calculating metabolic rates
Fundamentals 2013

$$M = \frac{21(0.23RQ + 0.77)Q_{O_2}}{A_D} \qquad (34)$$

where

M = metabolic rate, W/m2

RQ = respiratory quotient; molar ratio of QCO_2 exhaled to QO_2 inhaled, dimensionless (common values: .83 - .85, depends on diet.)

QO_2 = volumetric rate of oxygen consumption at conditions (STPD) of 0°C, 101.325 kPa, mL/s

DuBois Skin surface area equation

$$A_D = 0.203\, H^{0.725}\, W^{0.425}$$

where

H is the body height in m

W is the body mass in kg

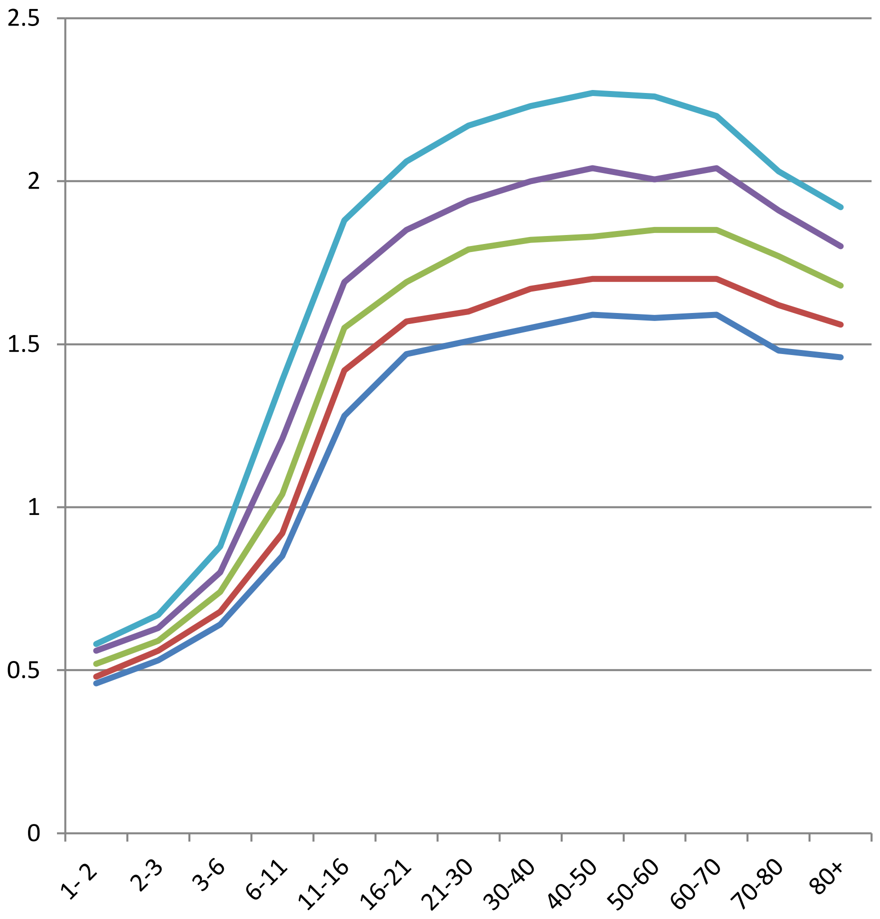
ASHRAE Fundamentals Ch 09, ASTM D6245

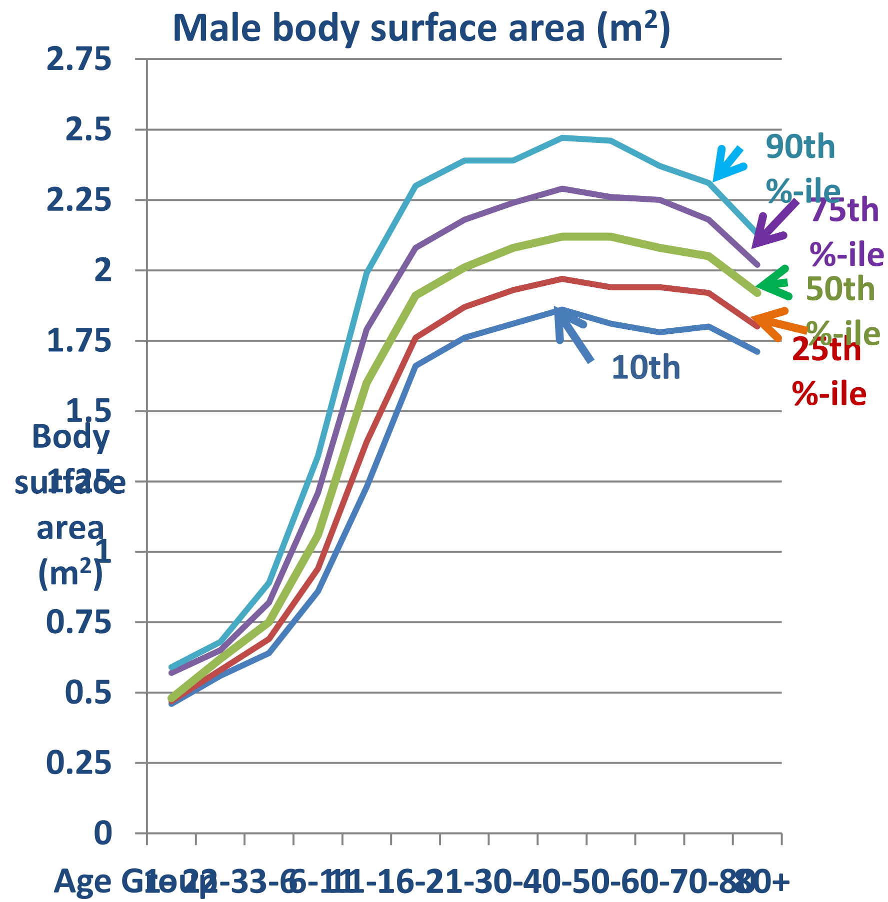
Body surface area data

"This is based on the average male European, with a skin surface area of about 1.8 m^2. For comparison, female Europeans have an average surface area of 1.6 m^2"

(ASHRAE Handbook Fundamentals 2013, page 9.1)

Adult body surface area by age
(calculated from EPA Exposure Factors Handbook 2011 data)





Does size matter?
Carbon dioxide generation rate
30-39 yo Median, 25th and 75th %ile

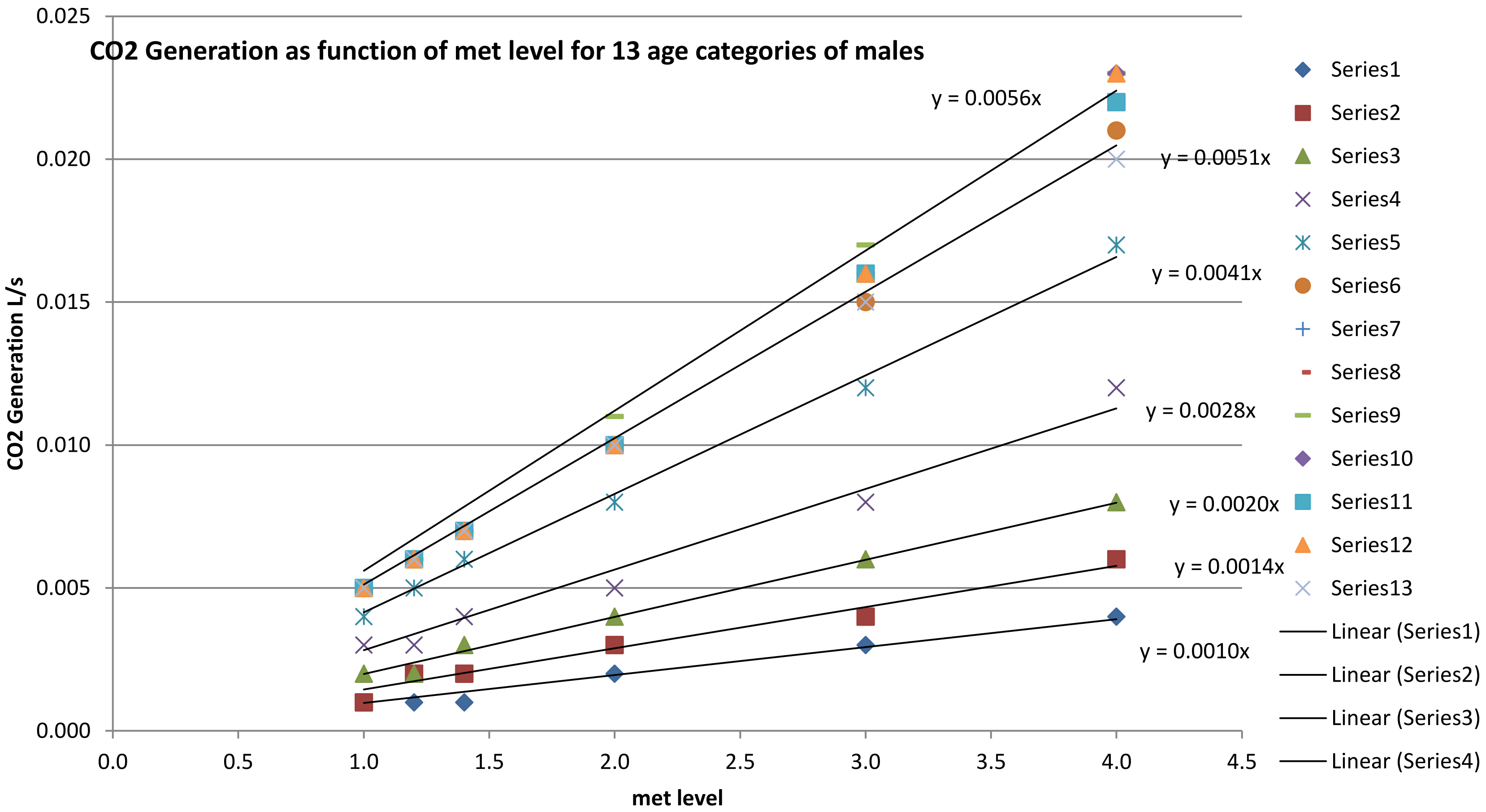
	MALES						FEMALES					
AGE	KG[a]	Height (m) [a]	A_D	G (L/s) @ 1.2 met	G (L/s) @ 1.6 met	G (L/s) @ 2.0 met	Kg[a]	Height (m) [a]	A_D	G (L/s) @ 1.2 met	G (L/s) @ 1.6 met	G (L/s) @ 2.0 met
6	24.3	1.193	0.8908	**0.002549**	**0.003398**	**0.004248**	23.6	1.192	0.8793	**0.002516**	**0.003354**	**0.004193**
7	26.7	1.254	0.9614	**0.002750**	**0.003667**	**0.004584**	26.8	1.246	0.9584	**0.002742**	**0.003656**	**0.004570**
8	31.3	1.316	1.0652	**0.003047**	**0.004063**	**0.005079**	31.9	1.33	1.0821	**0.003096**	**0.004127**	**0.005159**
9	36.6	1.379	1.1776	**0.003369**	**0.004492**	**0.005615**	35.5	1.37	1.1570	**0.003310**	**0.004413**	**0.005516**
10	40	1.423	1.2511	**0.003579**	**0.004772**	**0.005965**	41.1	1.445	1.2798	**0.003661**	**0.004882**	**0.006102**
11	46.6	1.499	1.3863	**0.003966**	**0.005288**	**0.006610**	47.5	1.504	1.4010	**0.004008**	**0.005344**	**0.006680**
12	51.5	1.546	1.4793	**0.004232**	**0.005643**	**0.007053**	52.3	1.561	1.4994	**0.004290**	**0.005720**	**0.007149**
13	59.2	1.637	1.6360	**0.004680**	**0.006240**	**0.007800**	56.8	1.6	1.5810	**0.004523**	**0.006031**	**0.007538**
14	63.9	1.685	1.7257	**0.004937**	**0.006583**	**0.008228**	61.6	1.616	1.6483	**0.004716**	**0.006287**	**0.007859**
15	70.1	1.738	1.8358	**0.005252**	**0.007002**	**0.008753**	63.3	1.629	1.6772	**0.004798**	**0.006398**	**0.007997**
15	75.1	1.751	1.9006	**0.005437**	**0.007250**	**0.009062**	62.4	1.622	1.6618	**0.004754**	**0.006339**	**0.007924**
17	77.4	1.759	1.9315	**0.005526**	**0.007367**	**0.009209**	63.7	1.631	1.6832	**0.004815**	**0.006420**	**0.008026**
18	81.3	1.764	1.9763	**0.005654**	**0.007538**	**0.009423**	65.4	1.631	1.7022	**0.004870**	**0.006493**	**0.008116**
19	79.5	1.778	1.9688	**0.005632**	**0.007510**	**0.009387**	68	1.633	1.7321	**0.004955**	**0.006607**	**0.008259**
20 years and over	75.4	1.759	1.9101	**0.005464**	**0.007286**	**0.009107**	75.4	1.621	1.8002	**0.005150**	**0.006867**	**0.008584**
20–29 years	73.4	1.763	1.8915	**0.005411**	**0.007215**	**0.009019**	73.4	1.631	1.7877	**0.005114**	**0.006819**	**0.008524**
30–39 years	76.7	176.4	54.3377	**0.155450**	**0.207267**	**0.259084**	76.7	1.634	1.8239	**0.005218**	**0.006957**	**0.008696**
30-39 yr 25%ile	75.4	171.5	52.8537	**0.151205**	**0.201607**	**0.252008**	62.5	1.586	1.6361	**0.004681**	**0.006241**	**0.007801**
30-39 yr 75th %ile	101.1	181.8	62.4563	**0.178676**	**0.238235**	**0.297793**	88.1	1.719	2.0070	**0.005742**	**0.007655**	**0.009569**
40–49 years	76.2	1.768	1.9258	**0.005509**	**0.007346**	**0.009182**	76.2	1.631	1.8164	**0.005196**	**0.006929**	**0.008661**
50–59 years	77.1	1.766	1.9338	**0.005532**	**0.007376**	**0.009221**	77.1	1.622	1.8182	**0.005201**	**0.006935**	**0.008669**
60–69 years	77.4	1.749	1.9235	**0.005503**	**0.007337**	**0.009171**	77.4	1.616	1.8163	**0.005196**	**0.006928**	**0.008660**
70–79 years	74.8	1.732	1.8824	**0.005385**	**0.007180**	**0.008975**	74.8	1.591	1.7700	**0.005064**	**0.006751**	**0.008439**
80 years and over	64.9	1.707	1.7536	**0.005017**	**0.006689**	**0.008361**	64.9	1.559	1.6420	**0.004697**	**0.006263**	**0.007829**

Does size matter?
Carbon dioxide generation rate
30-39 yo Median, 25th and 75th %ile

carbon dioxide generation rates by size and met level

	MALES						FEMALES					
				G (L/s)	G (L/s)	G (L/s)				G (L/s)	G (L/s)	G (L/s)
	W (kg)	h (m)	A_D (m^2)	1.2 met	1.6 met	2.0 met	W (kg)	h (m)	AD (m2)	1.2 met	1.6 met	2.0 met
30–39 yo (med)	76.7	1.76	1.9280	0.005516	0.007354	0.009193	76.7	1.63	1.8239	0.005218	0.006957	0.008696
30-39 yo 25%ile	75.4	1.72	1.8753	0.005365	0.007153	0.008942	62.5	1.59	1.6361	0.004681	0.006241	0.007801
30-39 75th %ile	101	1.82	2.2160	0.006340	0.008453	0.010566	88.1	1.72	2.0070	0.005742	0.007655	0.009569

CO_2 gen rate for 13 age categories of males



1	2	3	4	5	6	7	8	9	10	11	12	13
<1	1-3	3-6	6-11	11-6	16-21	21-30	30-40	40-50	50-60	60-70	70-80	>80

metabolic rates:
Out of date and generally too low

- Based on data mostly from the 1960s before the advent of supersized meals and people (the obesity epidemic)

Has A_D changed since the 1960s?

You bet it has

Supersize me!

Spoiler warning:
The following slide is disgusting.

AVERT YOUR EYES IF YOU DO NOT TOLERATE DISGUSTING PICTURES. WE WILL TELL YOU WHEN YOU CAN LOOK AGAIN.

Has A_D changed since the 1960s?

You bet it has

Supersize me!

Vasodilation

(*2013 Fundamentals* 9.1)

The hypothalamus controls various physiological processes to regulate body temperature. Its control behavior is primarily

proportional to deviations from setpoint temperatures with some integral and derivative response aspects. The most important and often used physiological process is regulating blood flow to the skin: when internal temperatures rise above a set point, more blood is directed to the skin.

This vasodilation of skin blood vessels can increase skin blood flow by 15 times [from 1.7 mL/(s · m^2)) at resting comfort to 25 mL/(s · m^2)]

Averaging met levels over the time period of interest.

“It is permissible to use a time-weighted average metabolic rate for individuals with activities that vary over a period of one hour or less. For example, a person who typically spends 30 minutes out of each hour “lifting/packing,” 15 minutes “filing, standing,” and 15 minutes “walking about” has an average metabolic rate of $0.50 \times 2.1 + 0.25 \times 1.4 + 0.25 \times 1.7 = 1.8$ met.”

(Normative appendix A, Std 55.-2010.)

Note:

No weighting or consideration of the time to “recover” from the higher activity level when entering the lower one.

Importance of dynamic modeling "Transients"

- PMV calculations based on metabolic rates
  - [Insert equation here]
- Time lag from entering a space to stable met rate level
  - Varying estimates from 5 minutes to 20 minutes to 40 minutes by thermal comfort researchers (oral communication)
- Characteristic occupancy period at workstation or in classroom seat – 50 to 240 minutes
- Do people get up and move around during the theoretical 4-hour office work period? (coffee, water cooler, toilet use, talk to colleague, retrieve files or other materials.)
- What is the effect of a short met level excursion?

55-2010

Preface

"The standard previously allowed modest increases in operative temperature beyond the PMV-PPD ("Computer Model Method" in the standard) limits as a function of air speed and turbulence intensity. But field studies, including recently published work, show that occupants, especially when neutral or slightly warm, prefer higher air speeds than were previously allowed. In certain combinations of temperature ranges and personal factors, the preference for more air movement is greater than for less air movement. Addenda since 2004 included a new method for expressing and selecting air-speed limits, and alternatives for determining the boundaries of comfort at air speeds above 0.15 m/s (30 fpm). With these changes, the standard continues to focus on defining the range of indoor thermal environmental conditions acceptable to a majority of occupants, but accommodates an ever increasing variety of design solutions intended both to provide comfort and to respect today's imperative for sustainable buildings."

55-2010

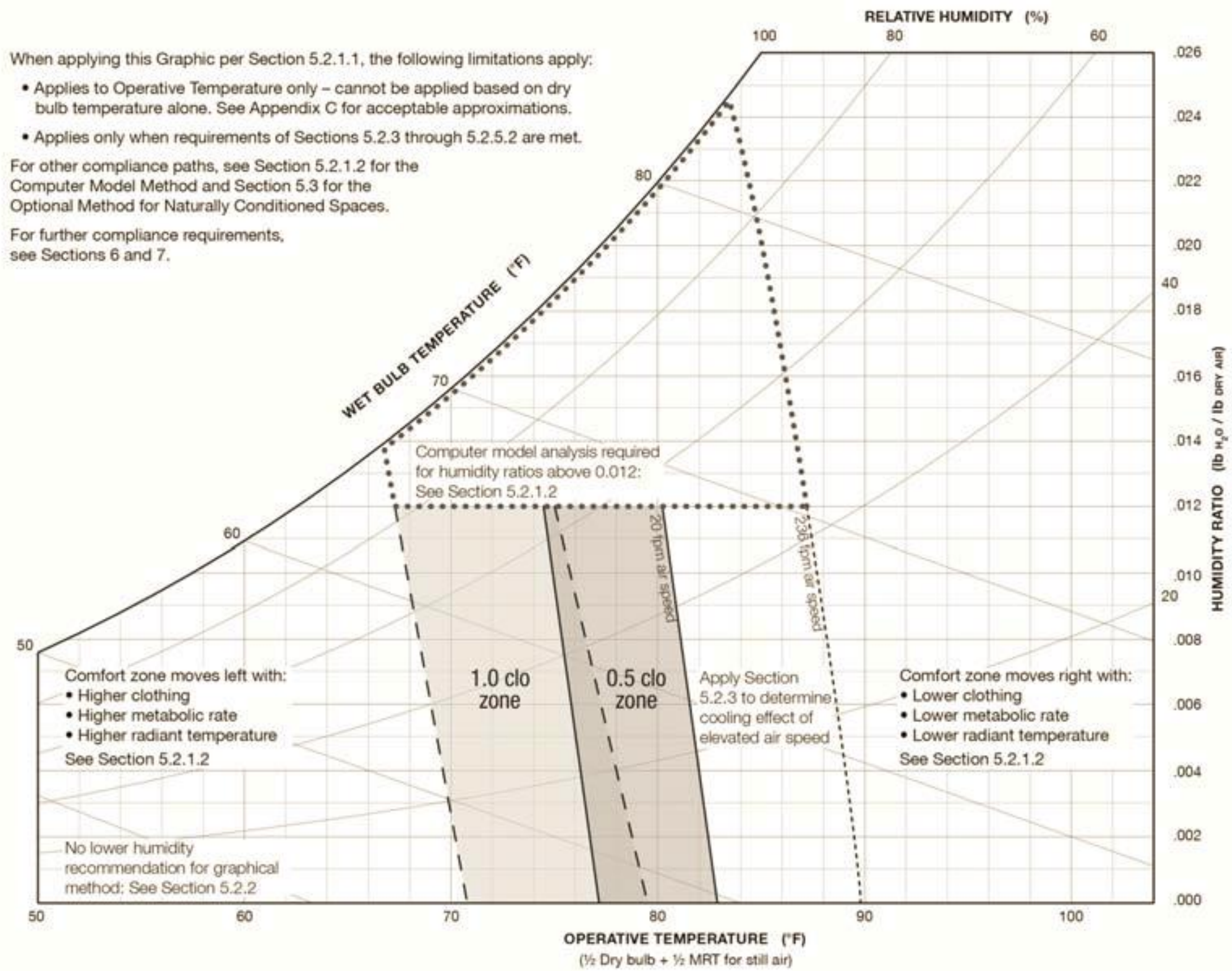


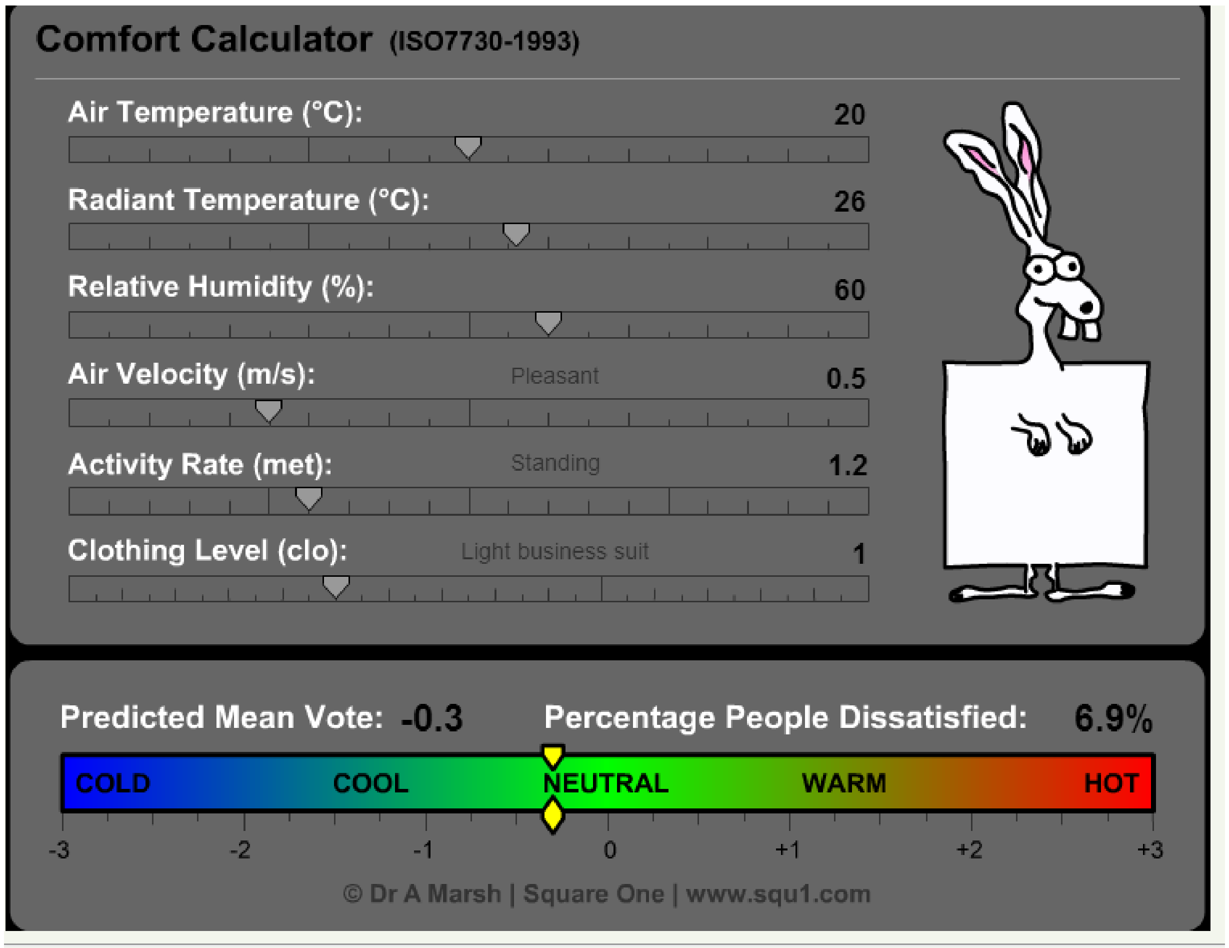
Figure 5.2.1.1 (IP) Acceptable range of operative temperature and humidity for spaces that meet the criteria specified in Section 5.2.1.1.
1.1 met, 0.5 & 1.0 clo

predicted mean vote (PMV):

an index that predicts the mean value of the votes of a large group of persons on the seven point thermal sensation scale.

- 2.5 walking
  - walking from house to car or bus, from car or bus to go places, from car or bus to and from the worksite
- 1.8 sitting, in class, general, including note-taking or class discussion
- 1.3 sitting, studying, general, including reading and/or writing, light effort

1.2 met



Comfort Calculator (ISO7730-1993)
Air Temperature (°C):
20
Radiant Temperature (°C):
26
Relative Humidity (%):
60
Air Velocity (m/s):
Pleasant
0.5
Activity Rate (met):
Standing
1.2
Clothing Level (clo):
Light business suit
1
Predicted Mean Vote: -0.3
Percentage People Dissatisfied: 6.9%
COLD
COOL
NEUTRAL
WARM
HOT
-3
-2
-1
0
+1
+2
+3
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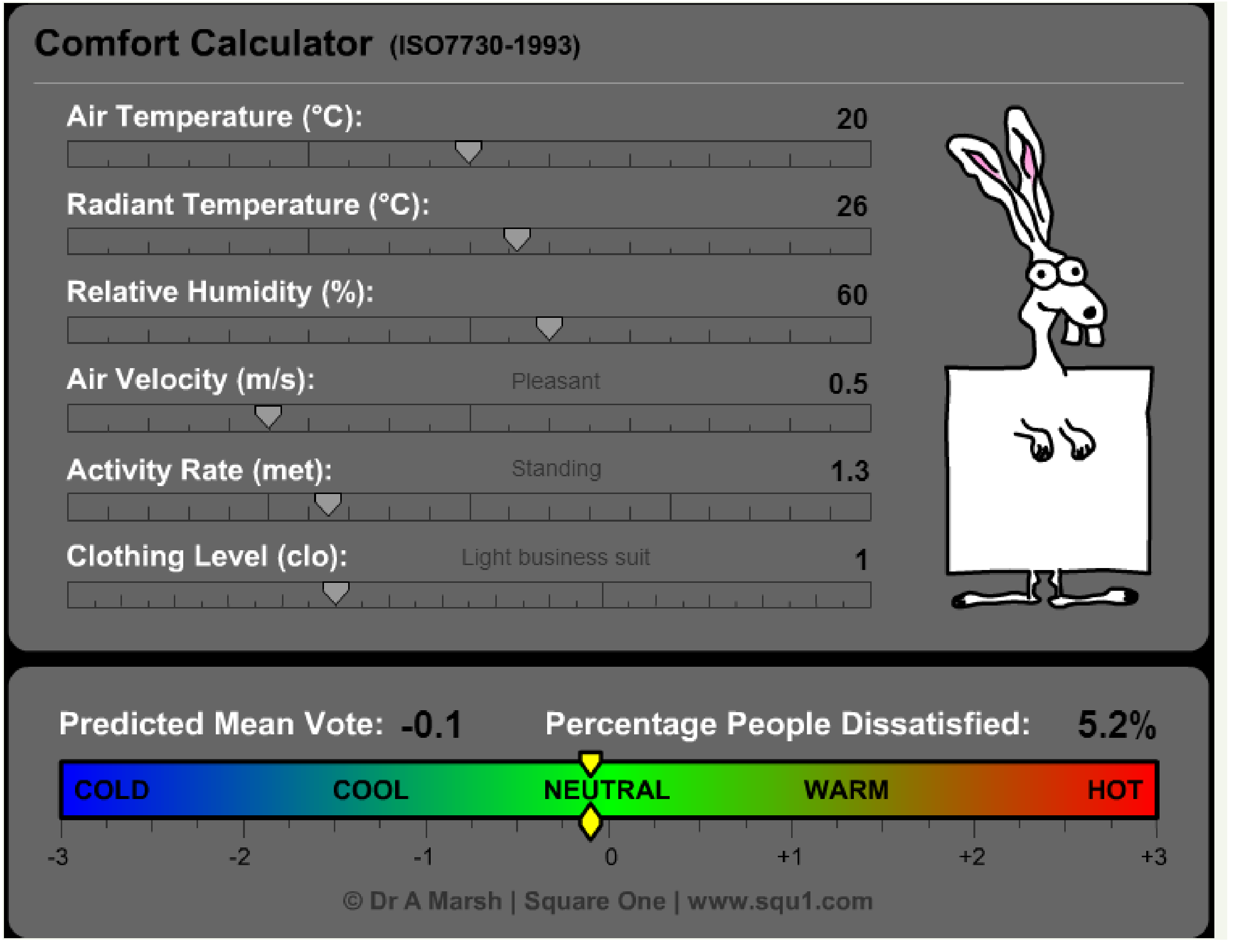
1.3 met


Comfort Calculator (ISO7730-1993)
Air Temperature (°C): 20
Radiant Temperature (°C): 26
Relative Humidity (%): 60
Air Velocity (m/s): Pleasant 0.5
Activity Rate (met): Standing 1.3
Clothing Level (clo): Light business suit 1
Predicted Mean Vote: -0.1
Percentage People Dissatisfied: 5.2%
COLD
COOL
NEUTRAL
WARM
HOT
-3
-2
-1
0
+1
+2
+3
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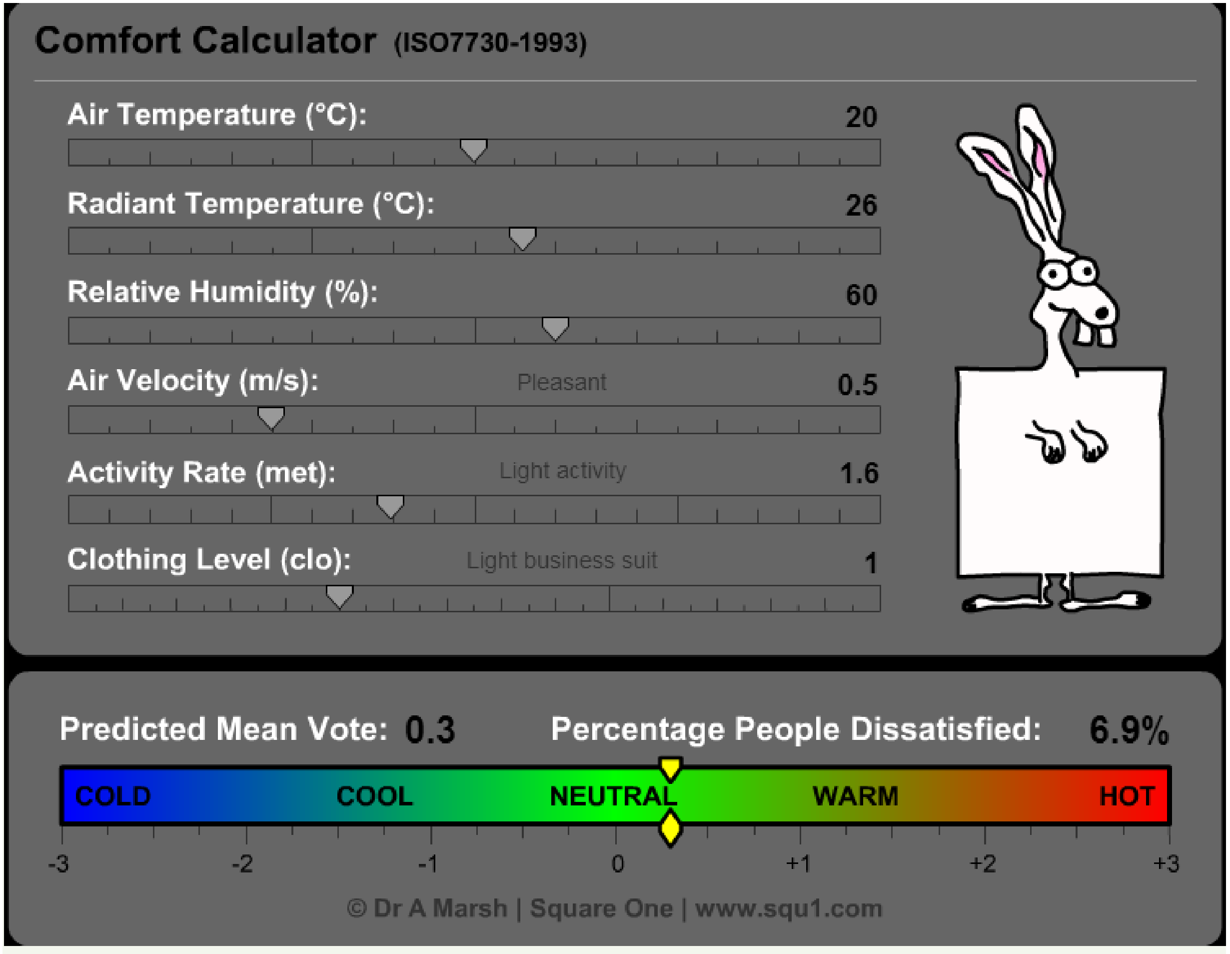
1.6 met


Comfort Calculator (ISO7730-1993)
Air Temperature (°C): 20
Radiant Temperature (°C): 26
Relative Humidity (%): 60
Air Velocity (m/s): Pleasant 0.5
Activity Rate (met): Light activity 1.6
Clothing Level (clo): Light business suit 1
Predicted Mean Vote: 0.3
Percentage People Dissatisfied: 6.9%
COLD
COOL
NEUTRAL
WARM
HOT
-3
-2
-1
0
+1
+2
+3
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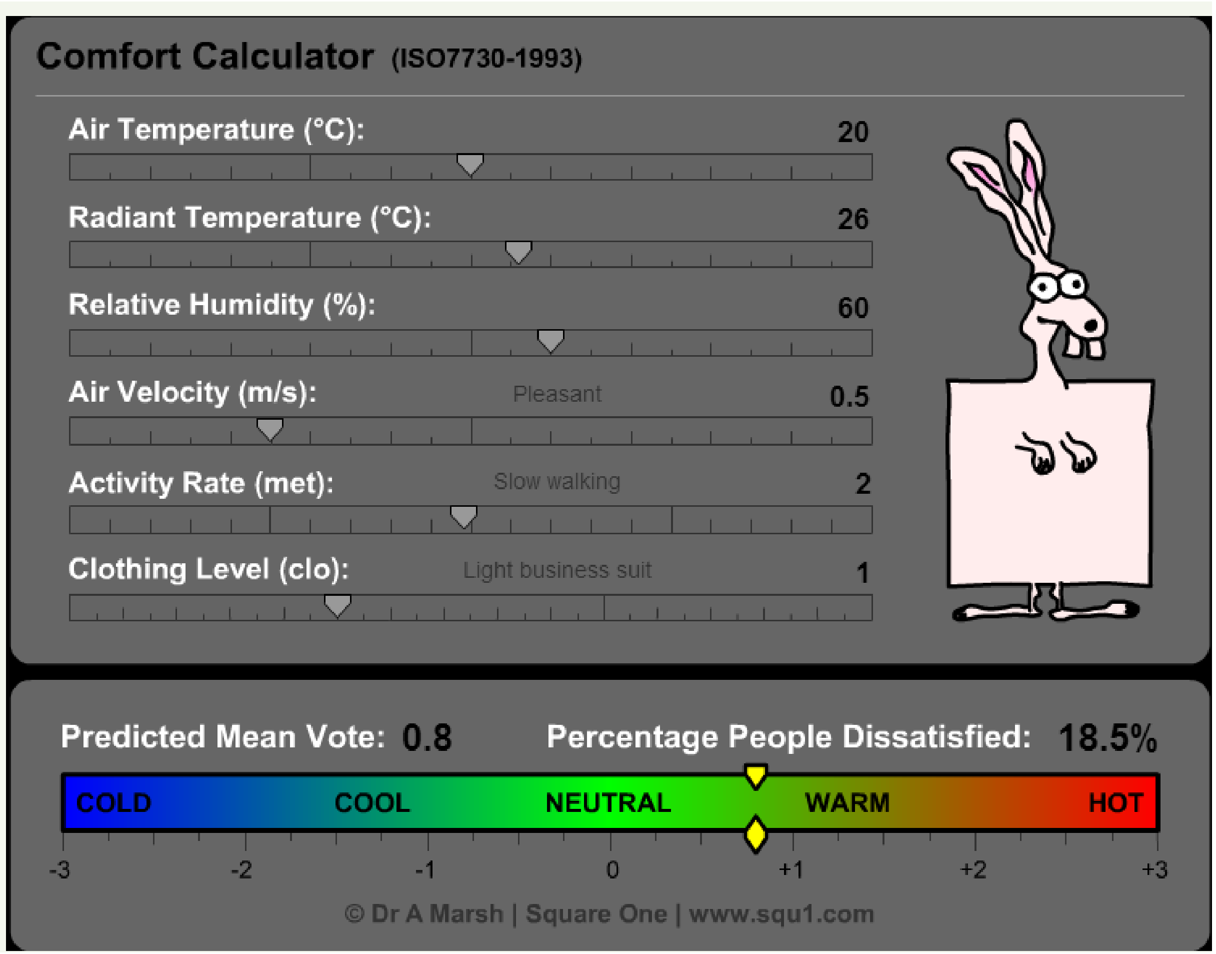
2.0 MET



Comfort Calculator (ISO7730-1993)
Air Temperature (°C): 20
Radiant Temperature (°C): 26
Relative Humidity (%): 60
Air Velocity (m/s): Pleasant 0.5
Activity Rate (met): Slow walking 2
Clothing Level (clo): Light business suit 1
Predicted Mean Vote: 0.8
Percentage People Dissatisfied: 18.5%
COLD
COOL
NEUTRAL
WARM
HOT
-3
-2
-1
0
+1
+2
+3
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55 vs 62
When do they apply?

- Std 62 is based on perceived IAQ upon first entering a space

- Std 55 seems to be more about people who have been in the space for a while and at fairly low metabolic levels.
- (since the occupants' metabolic rate may be quite different when the enter and when they have been there for a while. The designer is addressing the met level of the activities that happen in the space and not accounting for the changes a newly arriving occupant experiences.)

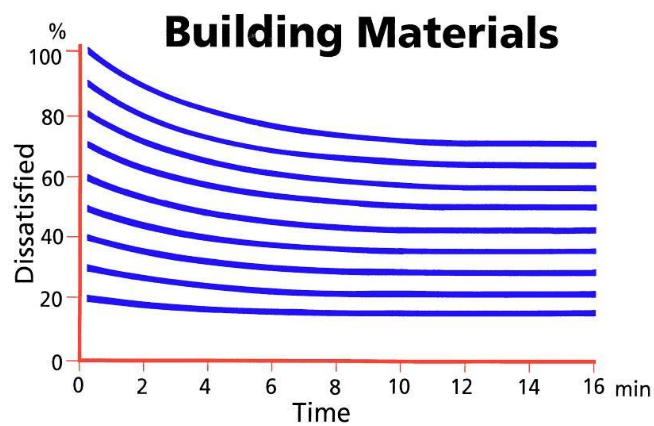
Std 55 – adapted people only?

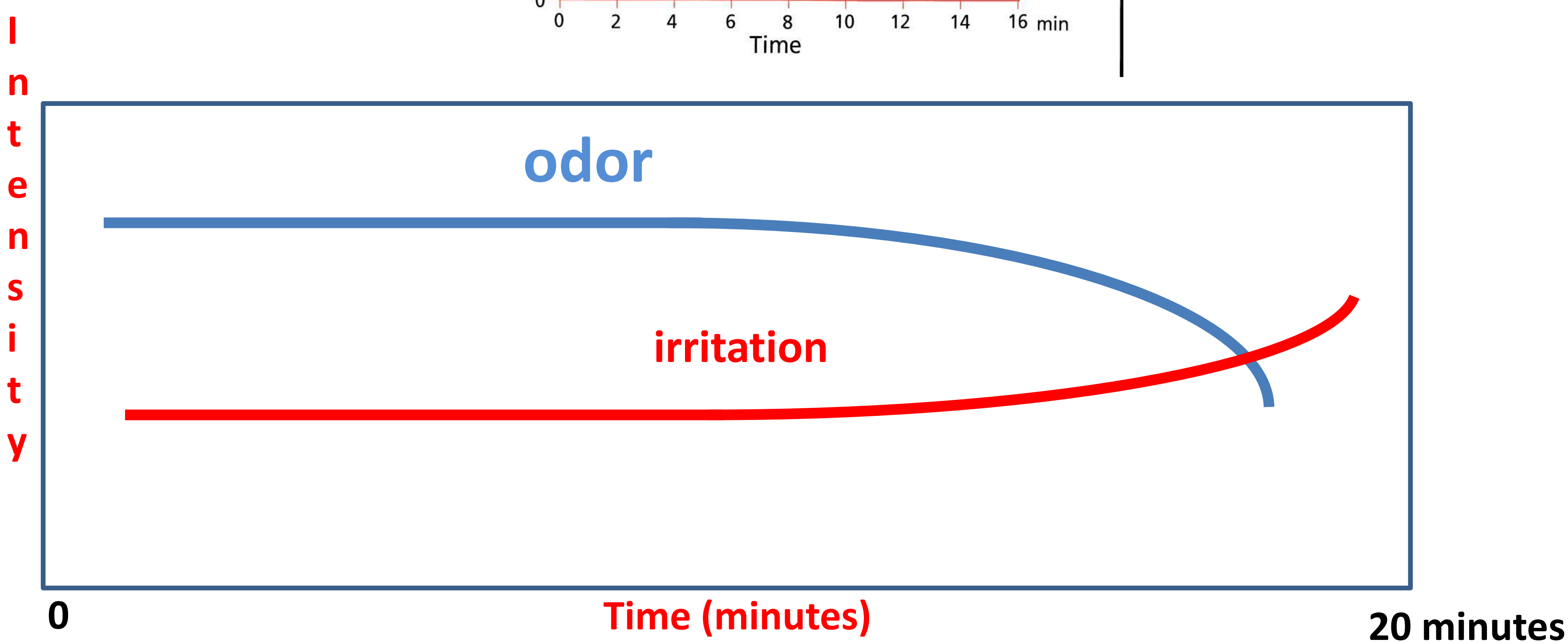
- Std 55 seems to be more about people who have been in the space for a while and at fairly low metabolic levels.
- (since the occupants' metabolic rate may be quite different when they enter and when they have been there for a while. The designer is addressing the met level of the activities that happen in the space and not accounting for the changes a newly arriving occupant experiences.)

55 vs 62

- Std 55 seems to be more about people who have been in the space for a while since the occupants' metabolic rate may be quite different when the enter and when they have been there for a while.
  - Enter a space at 25 C from outdoors when it is 30 C. It will feel very cool and comfortable – pleasantly cool. But after 10 or 15 or 20 or 30 minutes, 25 C will not feel cool to very many people, even with very low clo value and quiet activity (met = <1.3)

After 15 to 20 minutes, odor sensitivity diminishes and irritation effects rise (Gunnarsen, 1990?)





55 and 62? – GDL10

- The warmer the environment, the higher the emission rate of chemicals from surfaces
- The warmer the environment, the more sensitive people are to irritants
- The warmer the environment, the more allergenic at least one well-studied, common mold (A*spergillus*) becomes.

End here

Where does metabolism come in?

“A resting adult produces about 100 W of heat.” Because most of this is transferred to the environment through the skin, it is often convenient to characterize metabolic activity in terms of heat production per unit area of skin. For a resting person, this is about 58 W/m2 and is called 1 **met**. This is based on the average male European, with a skin surface area of about 1.8 m2. For comparison, female Europeans have an average surface area of 1.6 m2. Systematic differences in this parameter may occur between ethnic and geographical groups.” (ASHRAE *Handbook Fundamentals* 2013, p. 9.1)

- Sleeping adult: 0.95 met. (2011 Compendium of physical activity - https://sites.google.com/site/compendiumofphysicalactivities/compendia)
- =
- The body surface area A_D in m^2 can be estimated from the formula $A\ D = H^{0.203} * 0.725 W^{0.425}$ where *H* is the body height in m and W is the body mass in kg (*ASHRAE Handbook Fundamentals 2013, page 9.3*).

- Total body area (median) adults 21-79 y.o.
  = 2.0 – 2.15 (EPA Exposure Factors Handbook 2011)
  = 1.93 – 2.015 (CDC analysis of NHANES 2005-2006 data)

Table 4. Typical Metabolic Heat Generation for Various Activities W/m^2 met*
Resting: Sleeping 40 0.7; Reclining 45 0.8
Seated, quiet 60 1.0
Standing, relaxed 70 1.2
Walking (on level surface) 3.2 km/h (0.9 m/s) 115 2.0; 4.3 km/h (1.2 m/s) 150 2.6
6.4 km/h (1.8 m/s) 220 3.8
Office Activities
Reading, seated 55 1.0
Writing 60 1.0
Typing 65 1.1
Filing, seated 70 1.2
Filing, standing 80 1.4
Walking about 100 1.7
Lifting/packing 120 2.1
[*snip*]
Dancing, social 140 to 255 2.4 to 4.4
Tennis, singles 210 to 270 3.6 to 4.0
Basketball 290 to 440 5.0 to 7.6
Wrestling, competitive 410 to 505 7.0 to 8.7
Sources: Compiled from various sources. For additional information, **see Buskirk (1960),** Passmore and Durnin **(1967),** and Webb **(1964).*** 1 met = 58.1 W/m^2

Metabolic rates

A unit used to express the metabolic rate per unit DuBois area is the met, defined as the metabolic rate of a sedentary person (seated, quiet): 1 met = 58.1 W/m^2 = 50 $kcal/(h \cdot m^2)$.

A normal, healthy man at age 20 has a maximum capacity of approximately M_{act} = 12 met, which drops to 7 met at age 70. Maximum rates for women are on average about 30% lower. Long distance runners and trained athletes have maximum rates as high as 20 met.

An average 35year old who does not exercise has a maximum rate of about 10 met, and activities with M_{act} > 5 met are likely to prove exhausting.

For a resting person, this is about…

- Sleeping adult: 0.95 met. (2011 Compendium of physical activity - https://sites.google.com/site/compendiumofphysicalactivities/compendia)

- $58 W/m^2$ -->
  - 58 * 2.0 = 116 watts
  - 58 * 1.93 = 111.9 watts
  - 58 * 2.15 = 124.7 watts

  - "A resting adult produces about 100 W of heat." (ASHRAE *Handbook Fundamentals* 2013)

- One met for a resting oxygen consumption for a one man ±250 m L min^{-1} kg^{-1}
- For one woman ±200 mL min^{-1} kg^{-1}

- (250/60)*0.83 = 3.4583
- 3.333*
- 200/60)*0.83 = 3.333