HVAC in the real world: part 1

1st the big questions

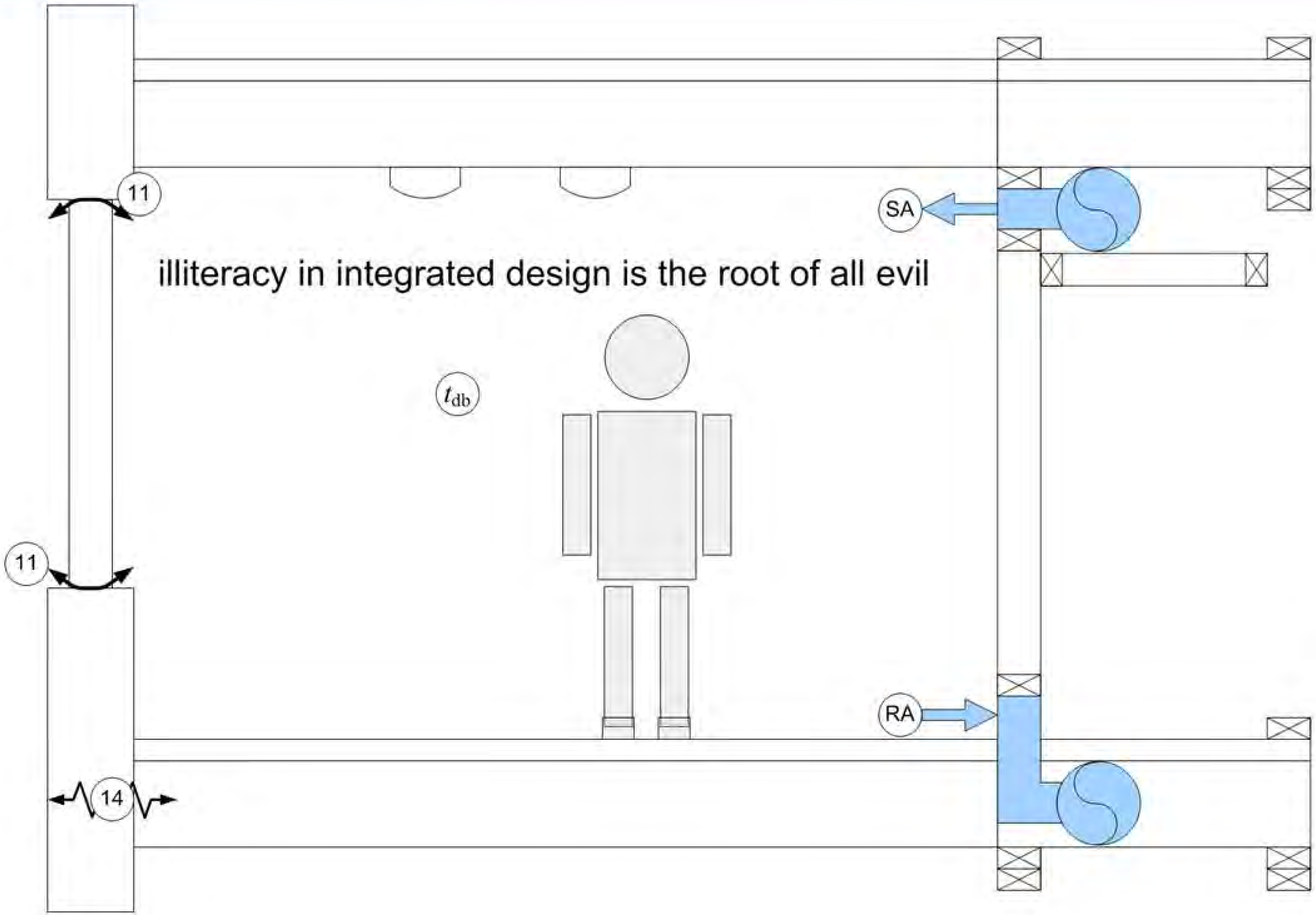
(bean's informal research)

Robert Bean, R.E.T., P.L. (Eng.)
President, Indoor Climate Consultants Inc
Technical Director, www.healthyheating.com
info@healthyheating.com

reality is…

comfort is…

illiteracy in indoor environmental engineering



to the illiterate

the world of

engineering

comfortable

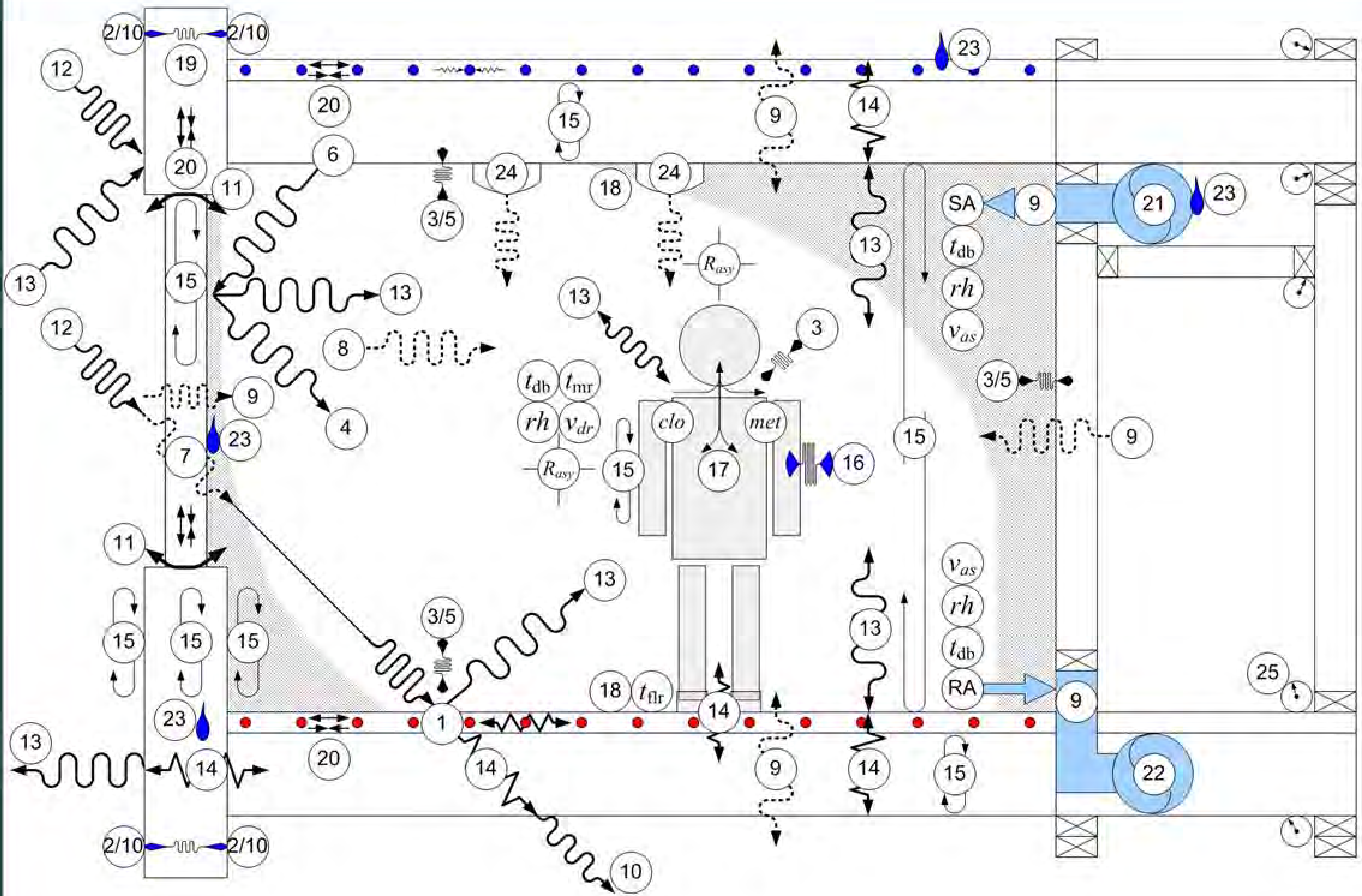
energy efficient

systems looks

like this

credit/source/resource (1)

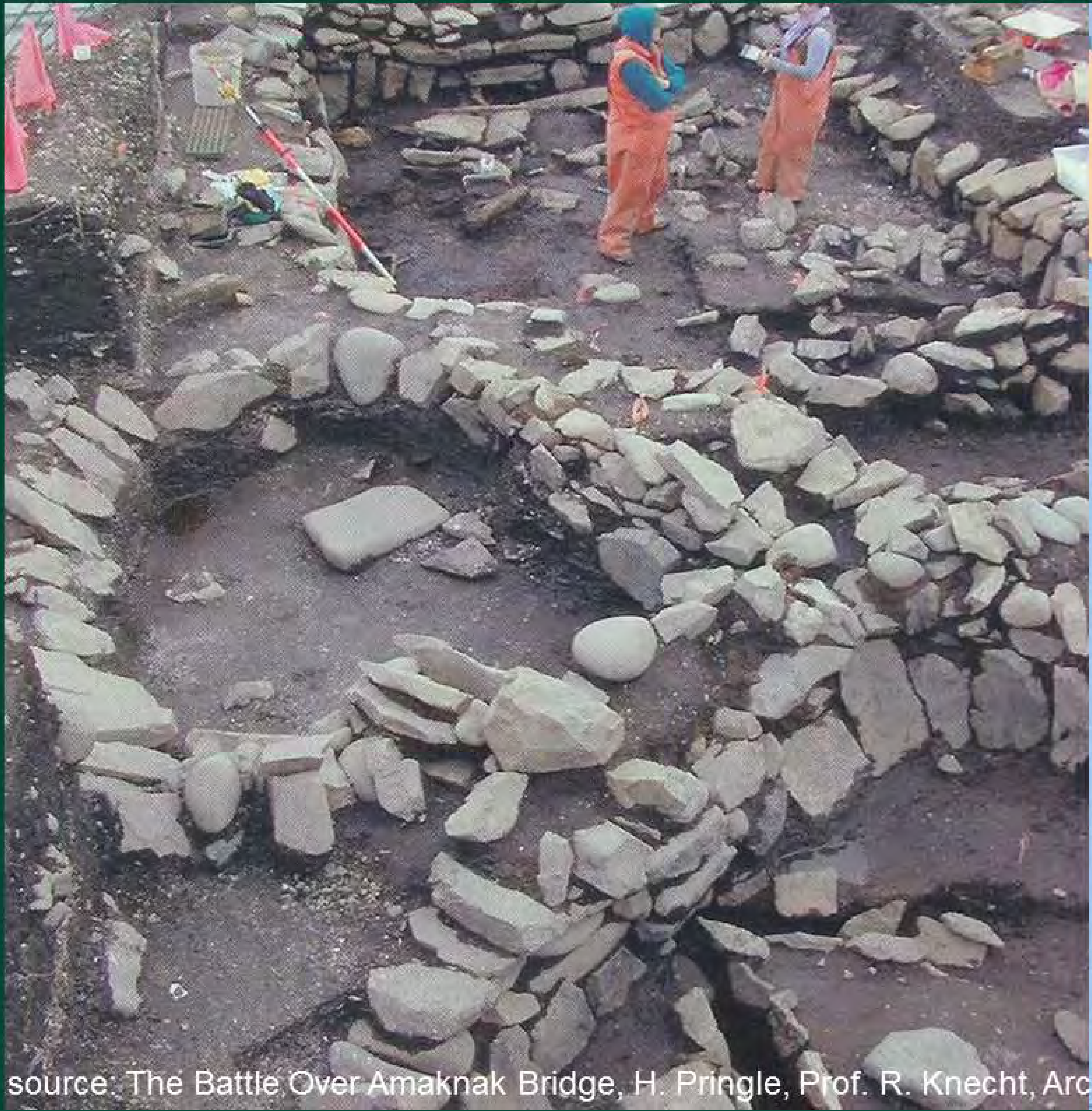
reality is…



to the educated the world of engineering comfortable energy efficient systems looks like this

credit/source/resource (1)

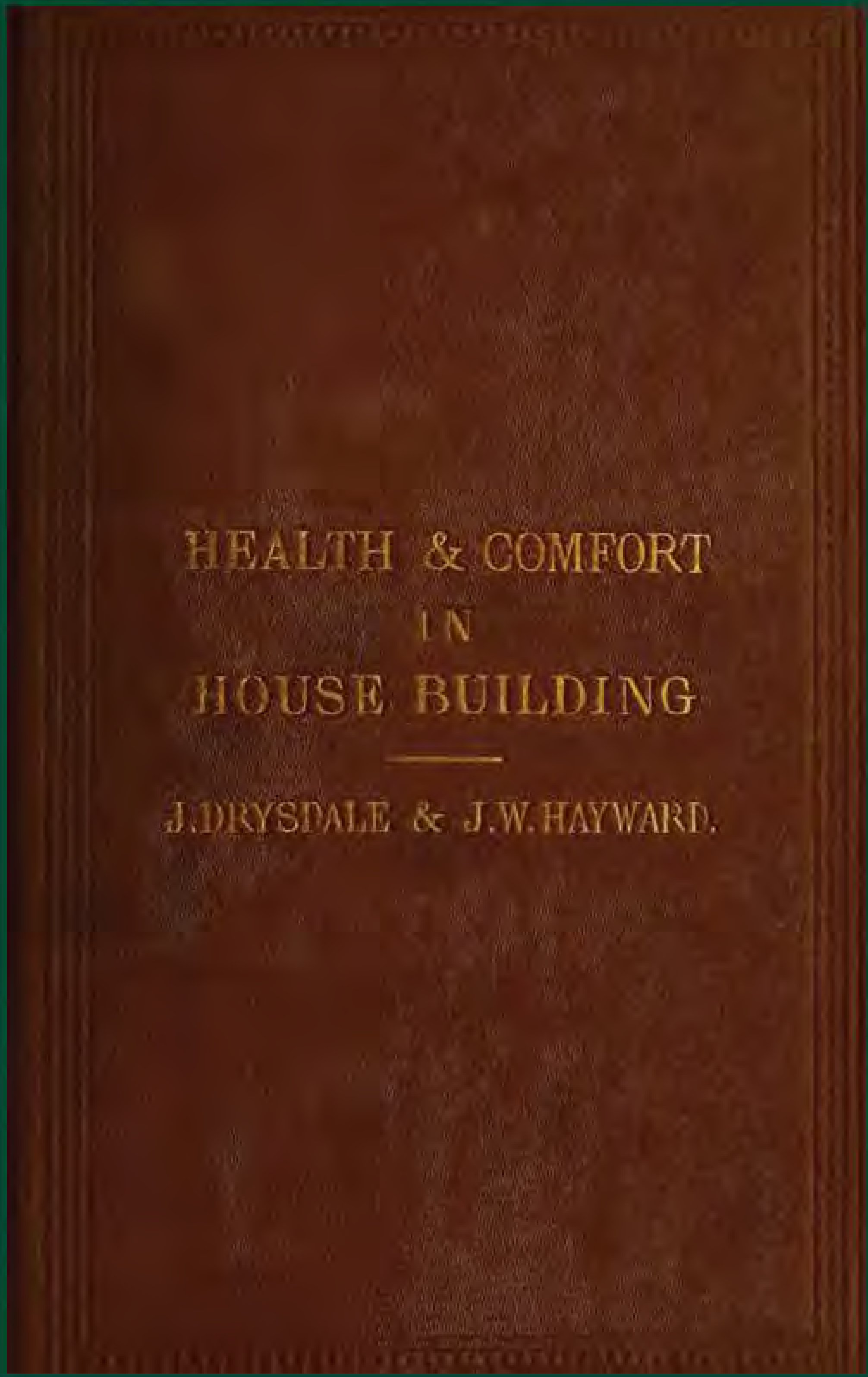
3000 years ago…

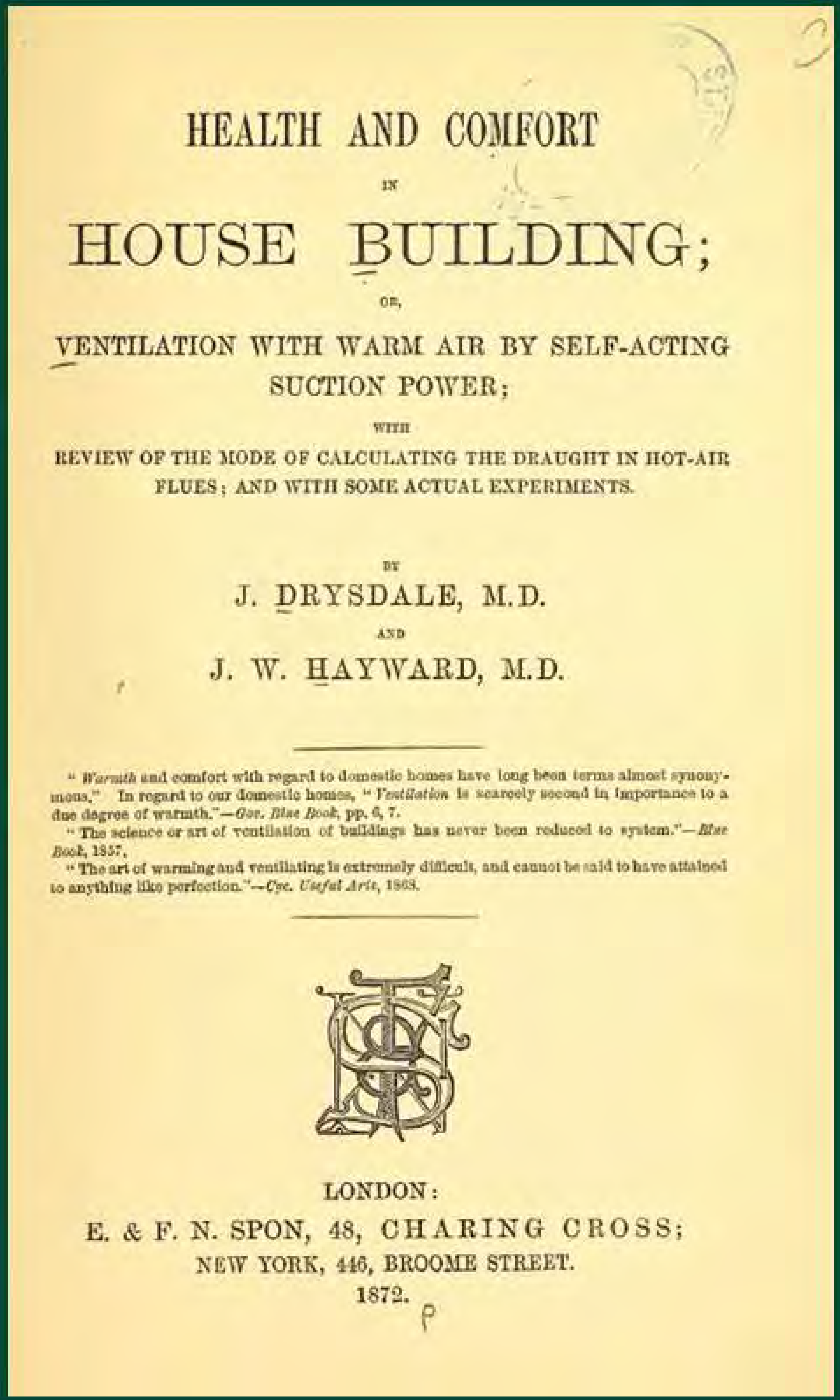


source: The Battle Over Amaknak Bridge, H. Pringle, Prof. R. Knecht, Archaeology, 2007

3000 years ago…

health & comfort in house building (c.1872)





HEALTH AND COMFORT

IN

HOUSE BUILDING;

OR,

VENTILATION WITH WARM AIR BY SELF-ACTING SUCTION POWER;

WITH

REVIEW OF THE MODE OF CALCULATING THE DRAUGHT IN HOT-AIR FLUES; AND WITH SOME ACTUAL EXPERIMENTS.

BY

J. DRYSDALE, M.D.

AND

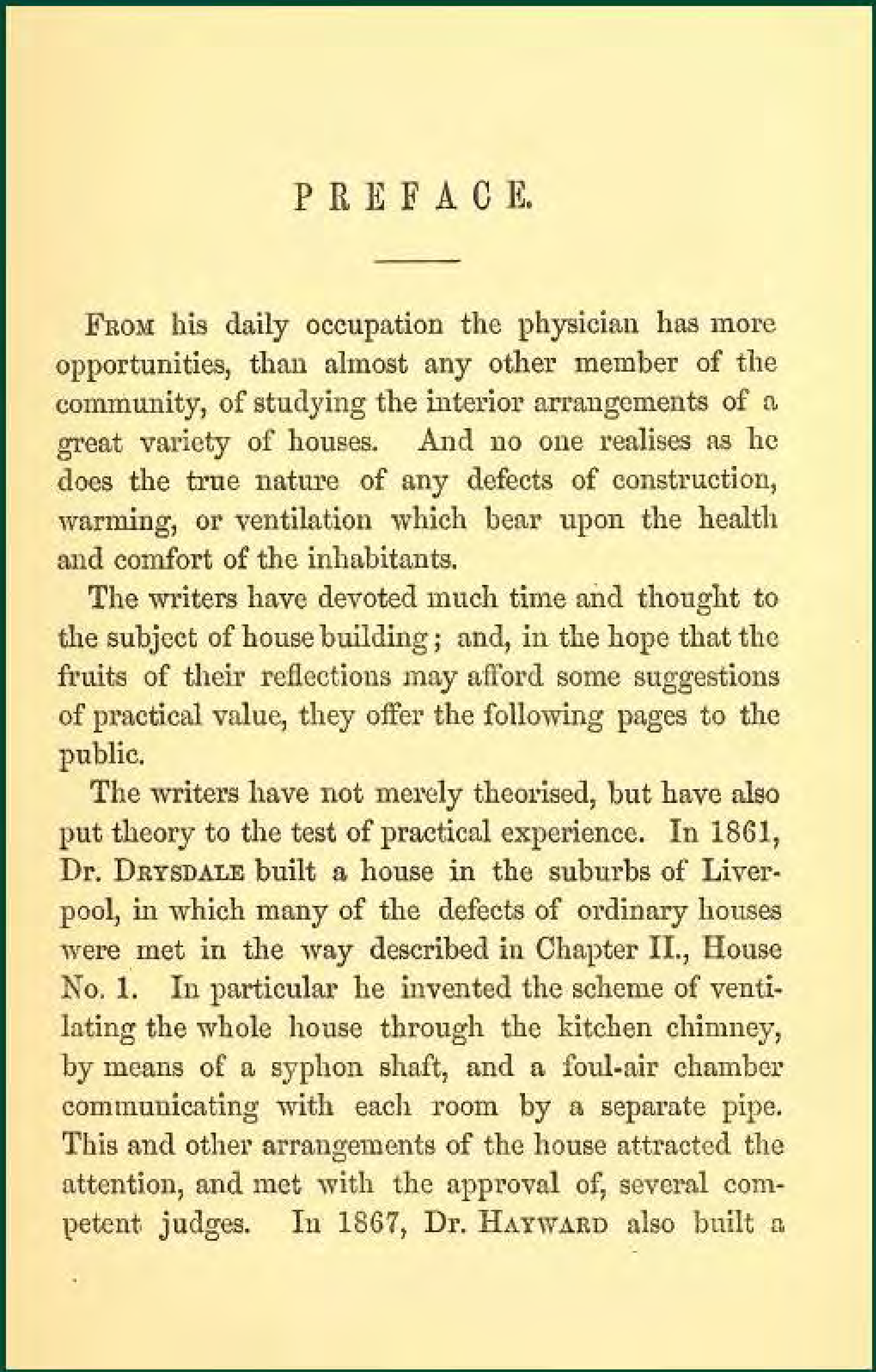
J. W. HAYWARD, M.D.

"*Warmth* and comfort with regard to domestic homes have long been terms almost synonymous." In regard to our domestic homes, "*Ventilation* is scarcely second in importance to a due degree of warmth."—*Gov. Blue Book*, pp. 6, 7.

"The science or art of ventilation of buildings has never been reduced to system."—*Blue Book*, 1857.

"The art of warming and ventilating is extremely difficult, and cannot be said to have attained to anything like perfection."—*Cyc. Useful Arts*, 1863.

LONDON:
E. & F. N. SPON, 48, CHARING CROSS;
NEW YORK, 446, BROOME STREET.
1872.



PREFACE.

FROM his daily occupation the physician has more opportunities, than almost any other member of the community, of studying the interior arrangements of a great variety of houses. And no one realises as he does the true nature of any defects of construction, warming, or ventilation which bear upon the health and comfort of the inhabitants.

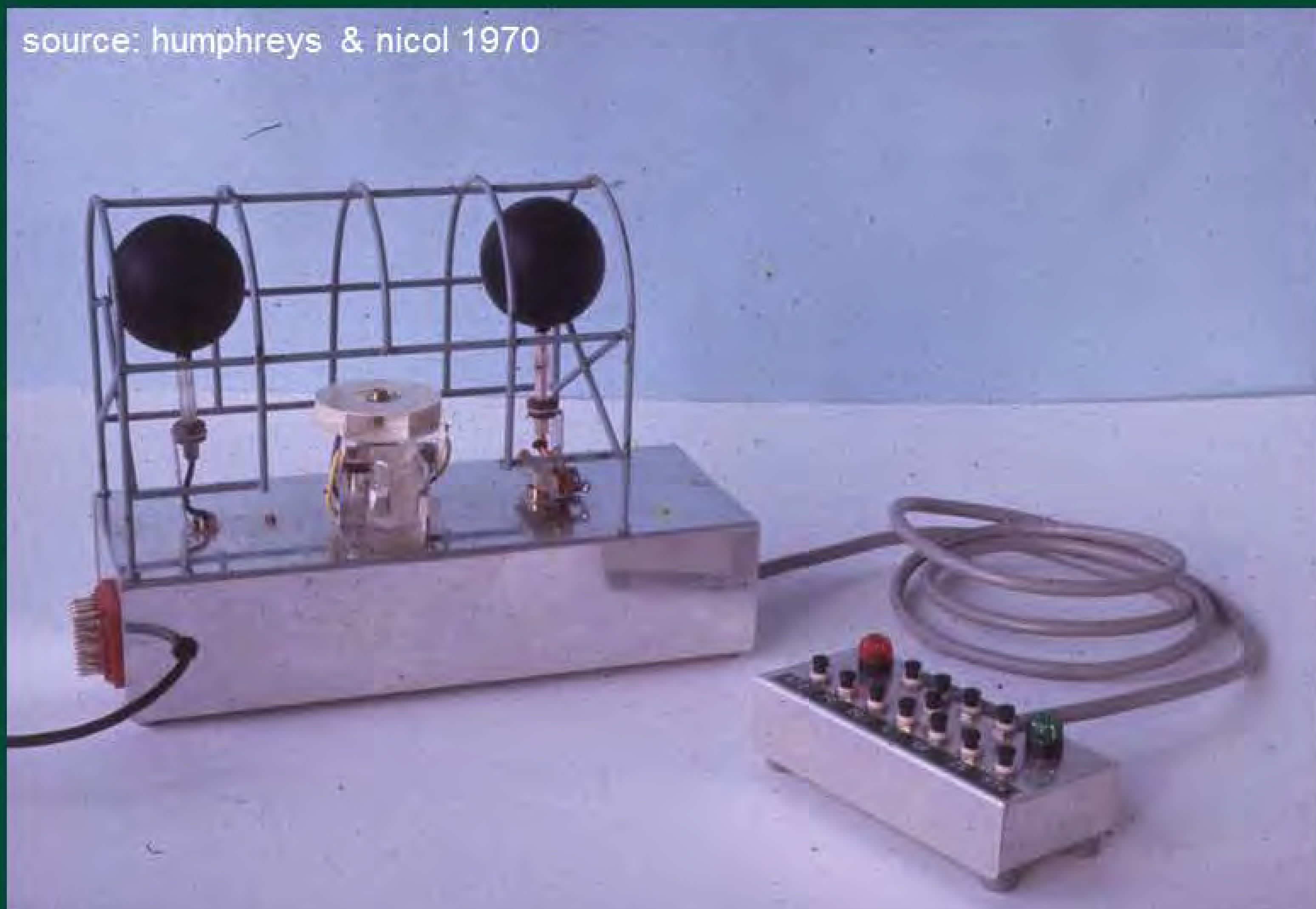
The writers have devoted much time and thought to the subject of house building; and, in the hope that the fruits of their reflections may afford some suggestions of practical value, they offer the following pages to the public.

The writers have not merely theorised, but have also put theory to the test of practical experience. In 1861, Dr. DRYSDALE built a house in the suburbs of Liverpool, in which many of the defects of ordinary houses were met in the way described in Chapter II., House No. 1. In particular he invented the scheme of ventilating the whole house through the kitchen chimney, by means of a syphon shaft, and a foul-air chamber communicating with each room by a separate pipe. This and other arrangements of the house attracted the attention, and met with the approval of, several competent judges. In 1867, Dr. HAYWARD also built a

thermal comfort research for dummies (c.1945)

thermal manikins come of age (c.1945)
photo credit: dr. r. goldman

thermal comfort POE turns analog (c.1965)



source: humphreys & nicol 1970

bre* data-logging project

charles g webb, initiated the first application of electronic data-logging and computer processing to comfort surveys (c.1965)

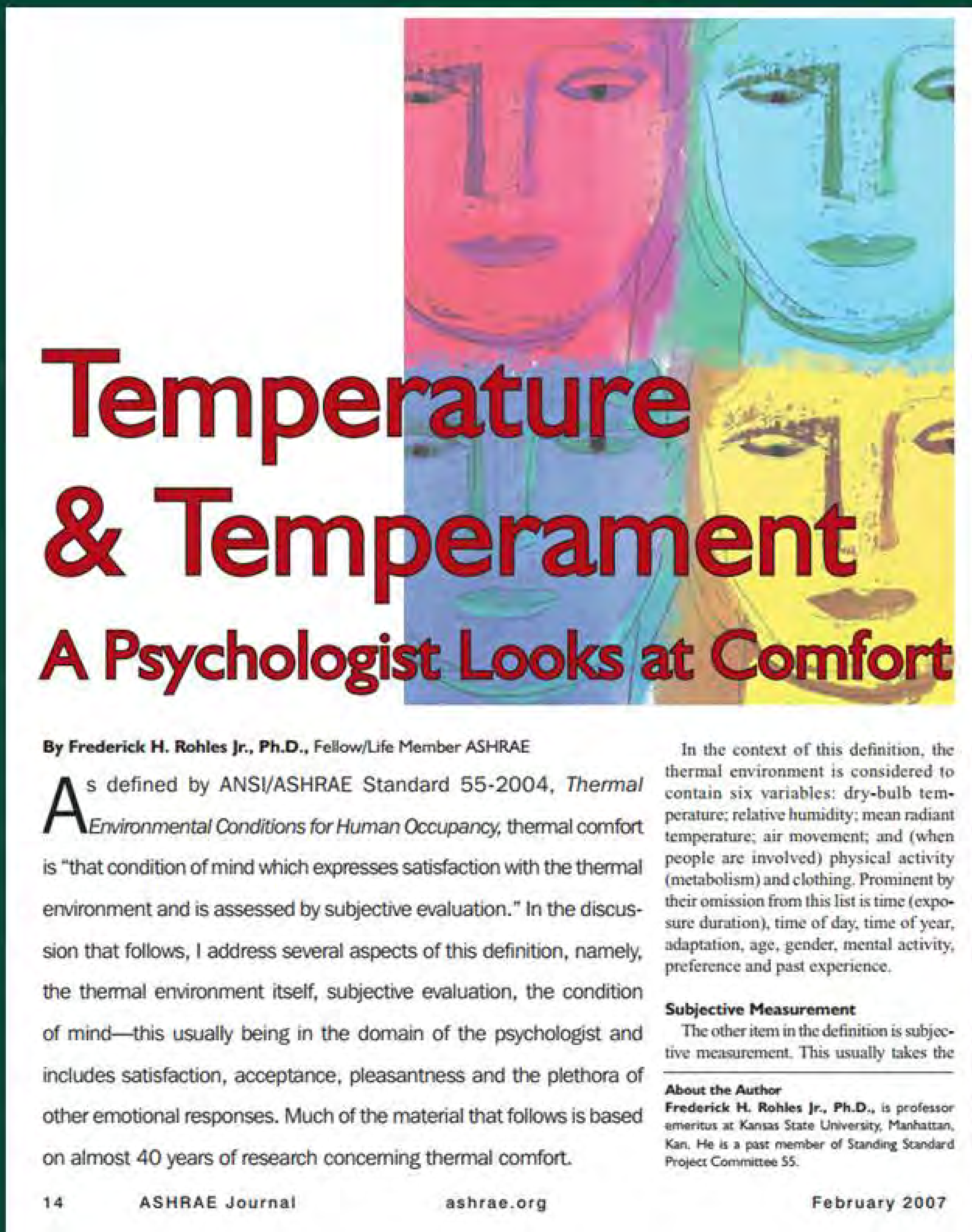
*building research establishment

how to pay off your student loans (c.1960-70)

credit/source: Olesen, B., Thermal Comfort, DTU environmental chamber, B&K, Technical Review #2

credit/source: Kansas State University, Institute for Environmental Research, KSU-ASHRAE Chamber

thermal comfort – is in your head



Temperature & Temperament

A Psychologist Looks at Comfort

By Frederick H. Rohles Jr., Ph.D., Fellow/Life Member ASHRAE

As defined by ANSI/ASHRAE Standard 55-2004, *Thermal Environmental Conditions for Human Occupancy,* thermal comfort is "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation." In the discussion that follows, I address several aspects of this definition, namely, the thermal environment itself, subjective evaluation, the condition of mind—this usually being in the domain of the psychologist and includes satisfaction, acceptance, pleasantness and the plethora of other emotional responses. Much of the material that follows is based on almost 40 years of research concerning thermal comfort.

In the context of this definition, the thermal environment is considered to contain six variables: dry-bulb temperature; relative humidity; mean radiant temperature; air movement; and (when people are involved) physical activity (metabolism) and clothing. Prominent by their omission from this list is time (exposure duration), time of day, time of year, adaptation, age, gender, mental activity, preference and past experience.

Subjective Measurement

The other item in the definition is subjective measurement. This usually takes the

About the Author

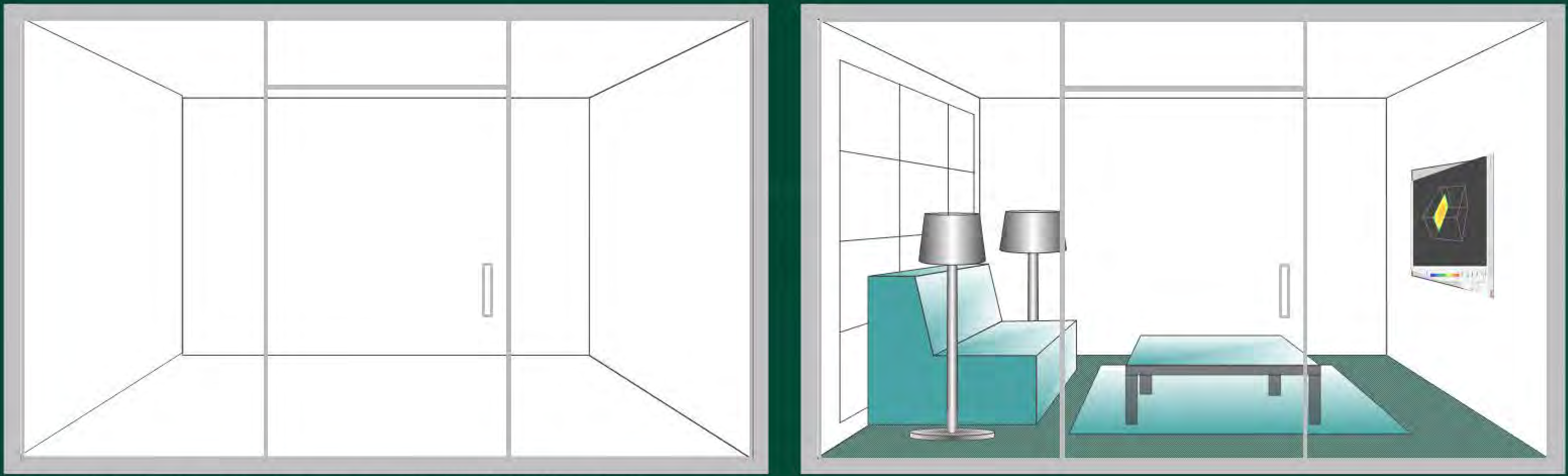
Frederick H. Rohles Jr., Ph.D., is professor emeritus at Kansas State University, Manhattan, Kan. He is a past member of Standing Standard Project Committee 55.

"To deny or ignore the psychology involved in comfort measurement is not only shortsighted, but treats the human subject as a machine, which it is not."

(Rohles,1980)

Credit/Source: Rohles, F.H., Temperature & Temperament, A Psychologist Looks at Comfort, ASHRAE Journal, February 2007

thermal comfort – it is in your head



Adapted/Credit: Bean, R., Radiant Based HVAC, ASHRAE D.L. Program, 2010

When it comes to meat lockers, "…adding the embellishments and changes was equivalent to raising the temperature two and one-half degrees."

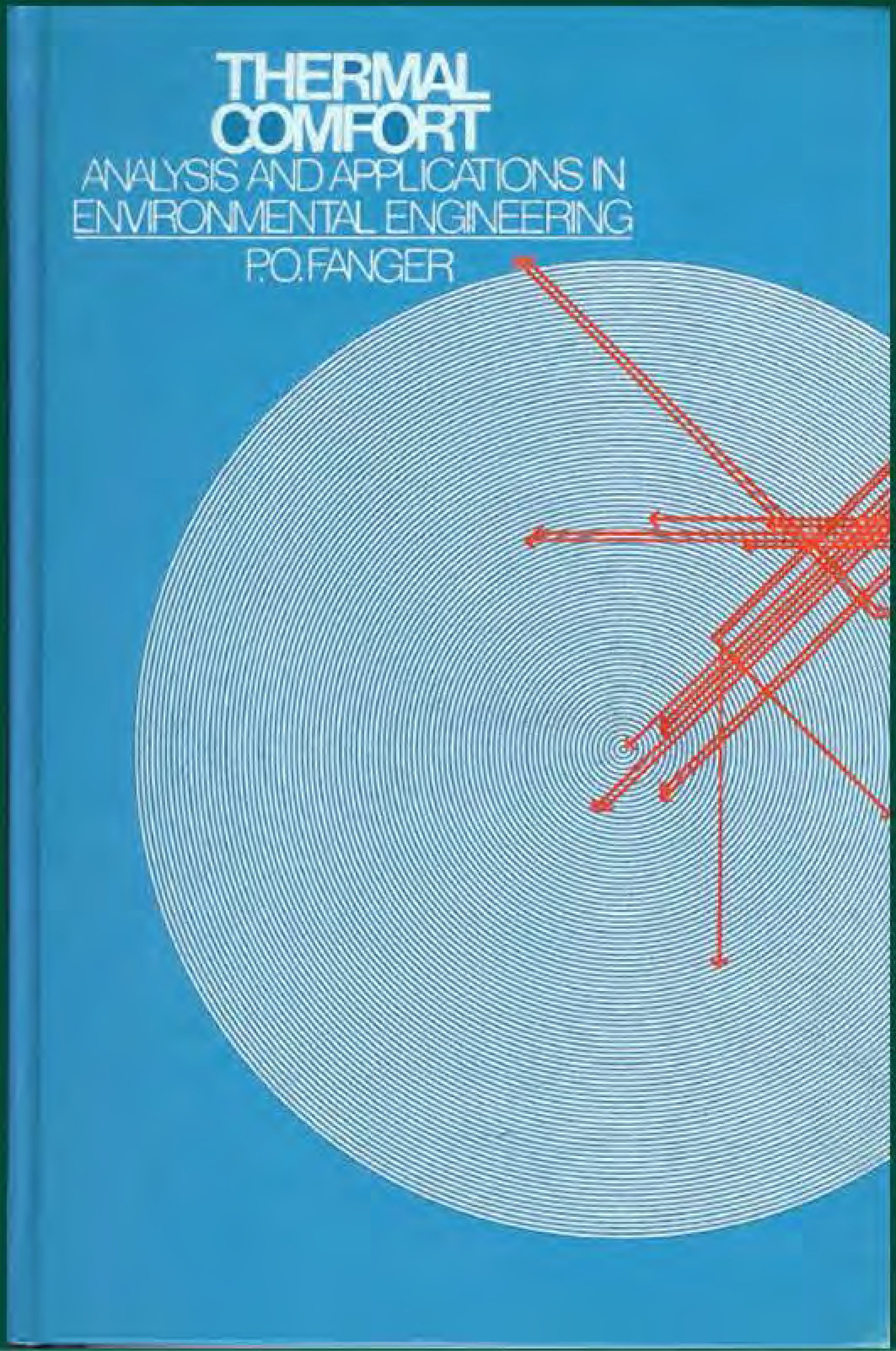
(adapted from Rohles 1980)

thermal comfort – it is in your head

"Do we feel differently when we know what the temperature of the room is than when we don't know what it is?" Prof. F. Rohles

simmonds, fanger, olesen

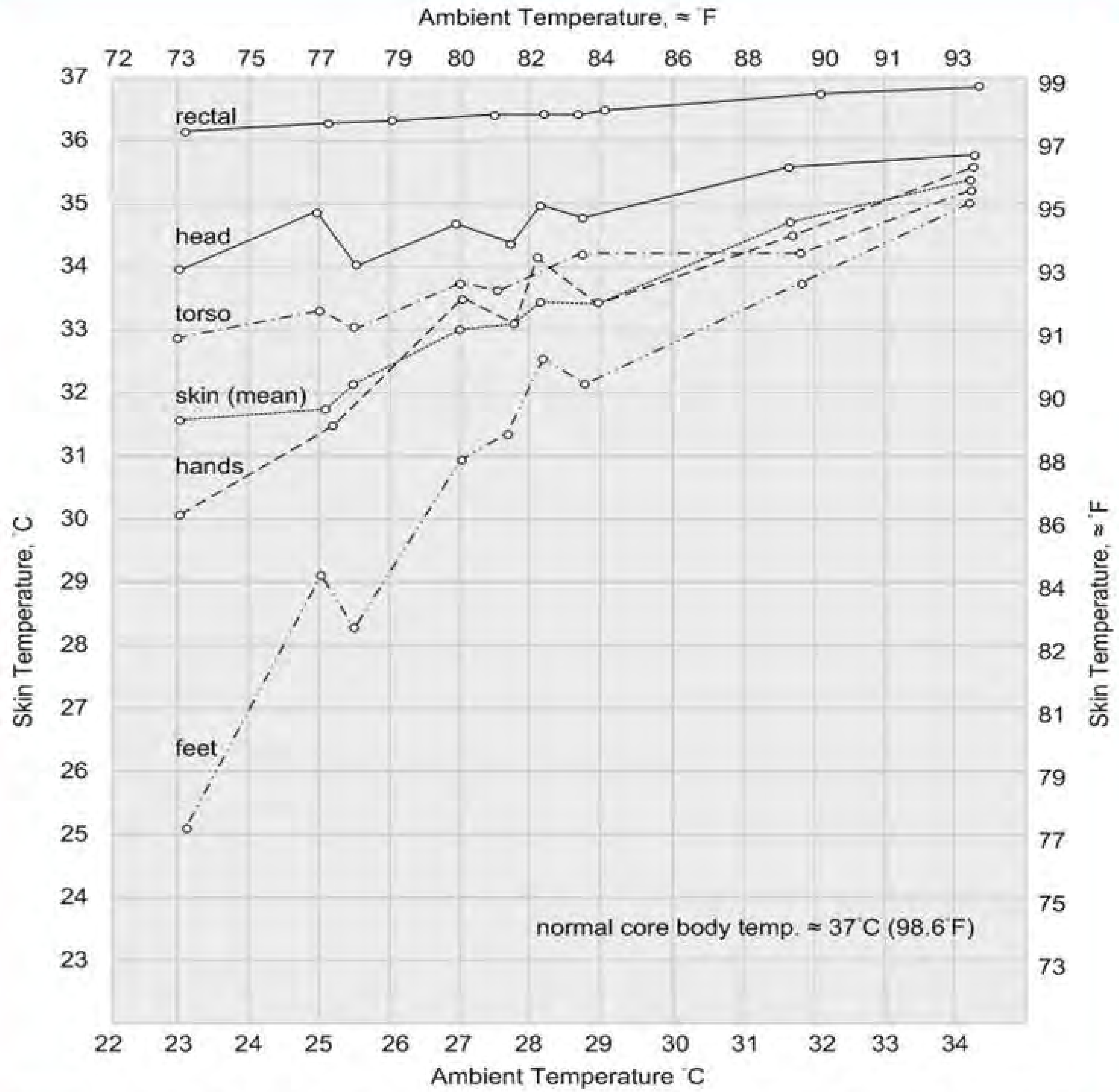
literally - an inside out approach (c.1970)



"…a rational calculation of heating and air-conditioning systems must begin with the conditions for comfort…"

fanger, p.o., thermal comfort: analysis and applications in environmental engineering, mcgraw-hill book company, 1970

ambient temperature & skin temperatures (c.1980)



Skin temperatures on different parts of a nude person measured at different ambient temperatures
Adapted from: Olesen, B.W., 1982, Thermal Comfort, Technical Review, Bruel & Kjaer

unlike core body temperatures skin temperatures vary considerably

skin temperatures on different parts of a nude person measured at different ambient temperatures, adapted from: olesen, b.w., thermal comfort, technical review, bruel & kjaer, 1982

seeing the invisible…(c. 1980 >>>)

seeing the invisible…(c. 1980 >>>)

#bscamp 2015

making sense of the sensible

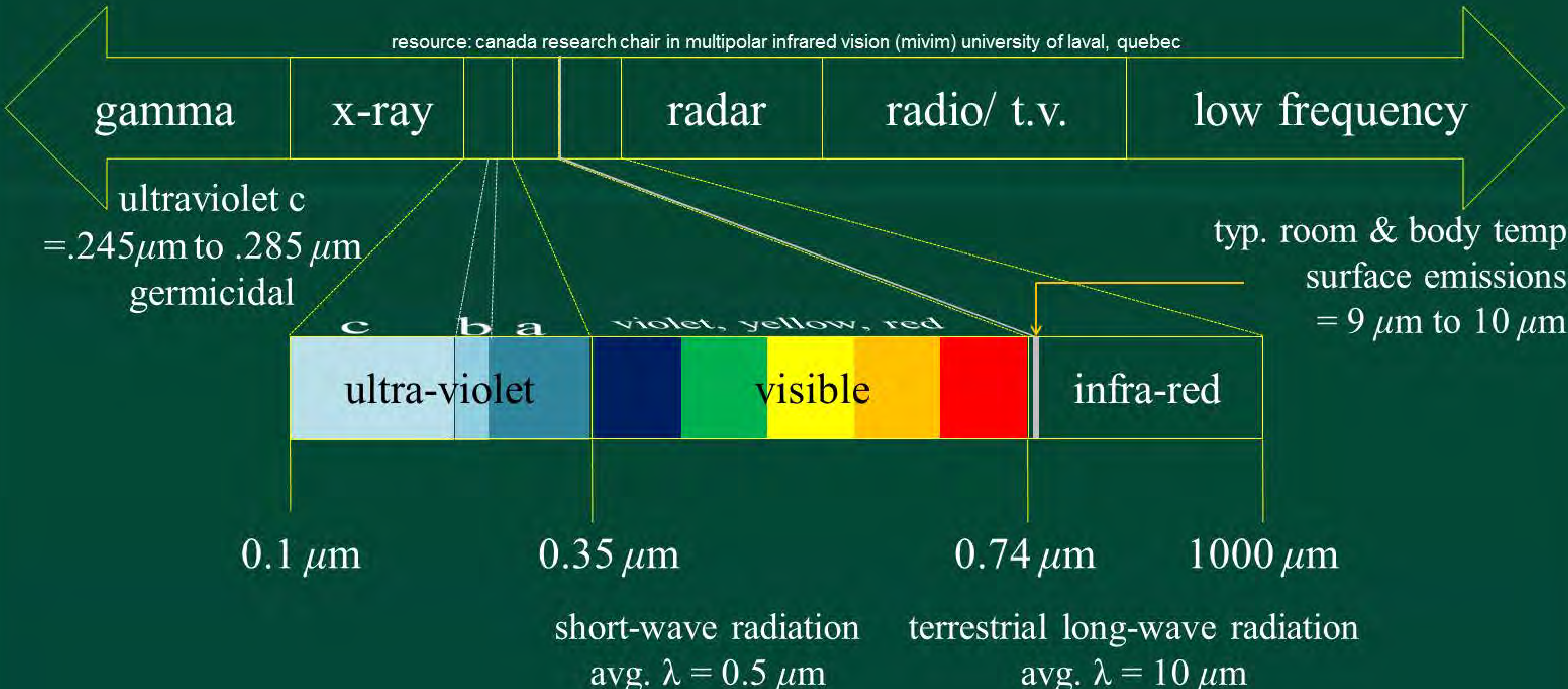
representative rates at which heat and moisture are given off by human beings in different states of activity

degree of activity	location	adult male Btu/h	adjusted, m/f[a] Btu/h	sensible Btu/h	latent Btu/h	% sensible heat that is radiant[b] low velocity	% sensible heat that is radiant[b] high velocity
seated at theater	theater, matinee	390	330	225	105	60	27
seated, very light work	offices, hotels, apartments	450	400	245	155		
moderately active office work	offices, hotels, apartments	475	450	250	200	58	38
walking, standing	drug store, bank	550	500	250	250		
heavy work	factory	1500	1450	580	870	54	19
athletics	gymnasium	2000	1800	710	1090		

radiant solutions to radiant problems

canyon de chelly, arizona
source credit: 2009 by mary caris.

a very small slice of energy

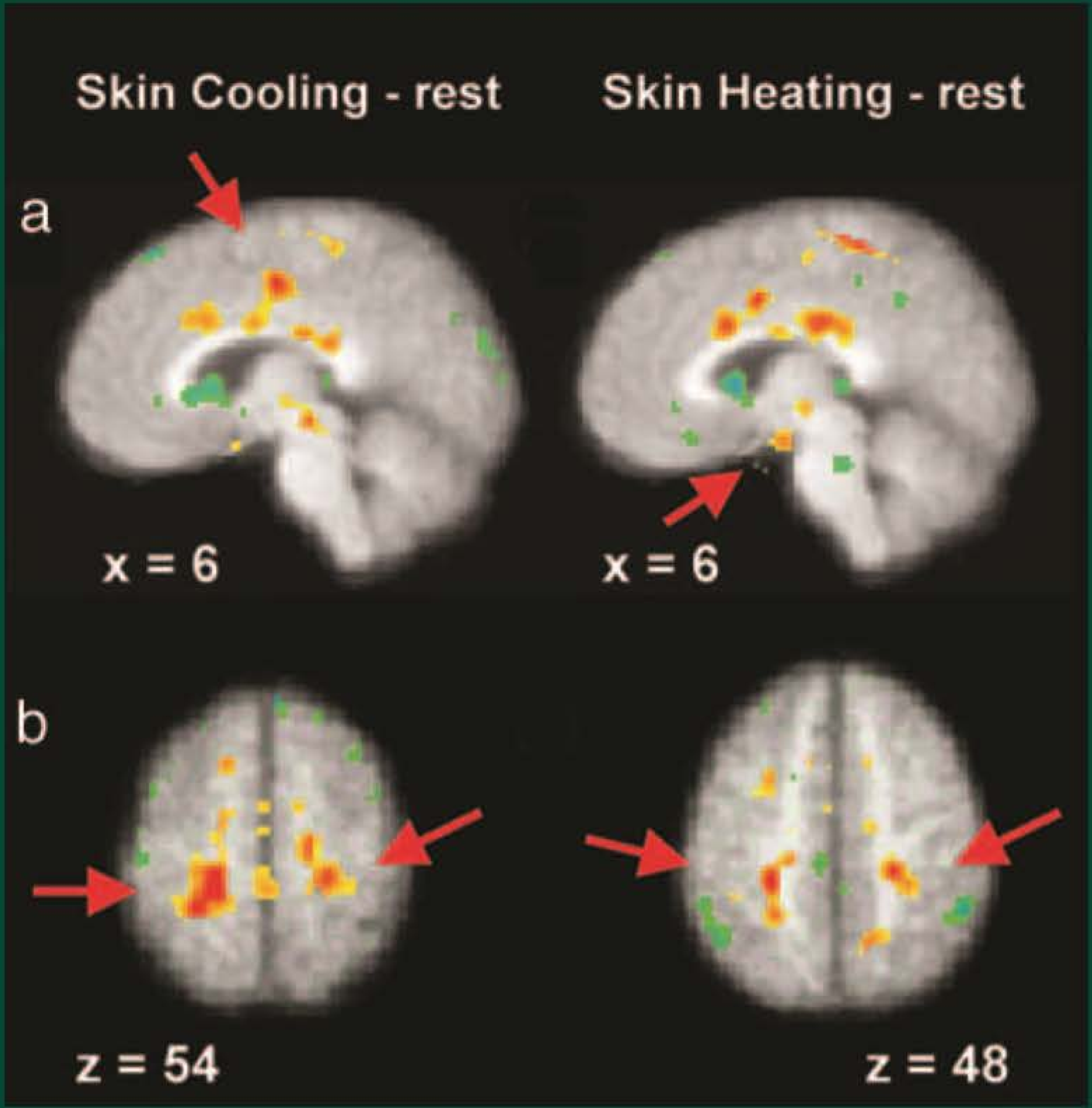


emissivity / absorptivity

credit: martin dohrn/science photo library.

credit: eye of science/science photo library.

the autonomic and endocrine system at work



in heating

warm surfaces suppress

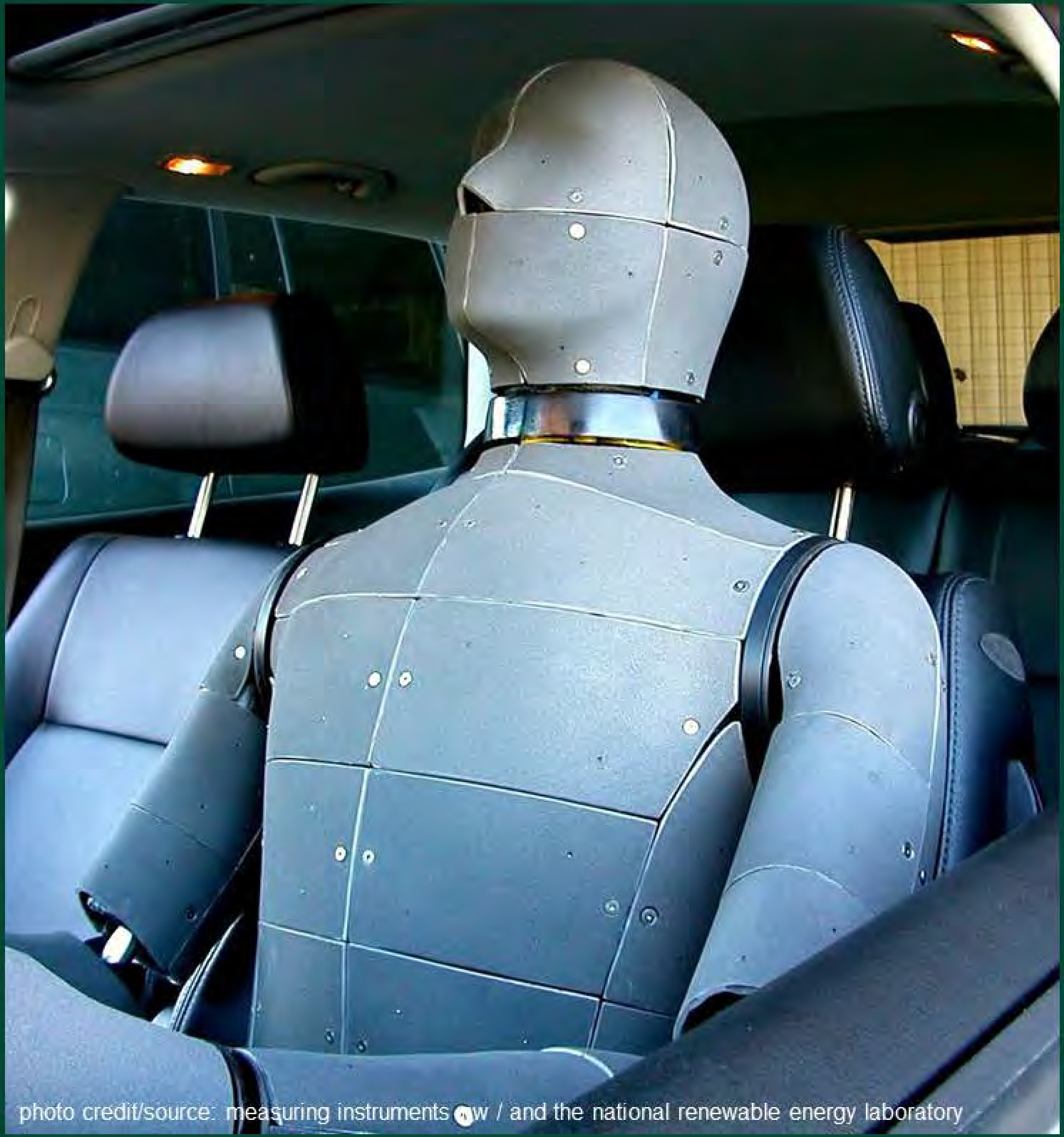
the loss of body heat

in cooling

cool surfaces enable the

loss of body heat

the real million dollar man



meet

adam

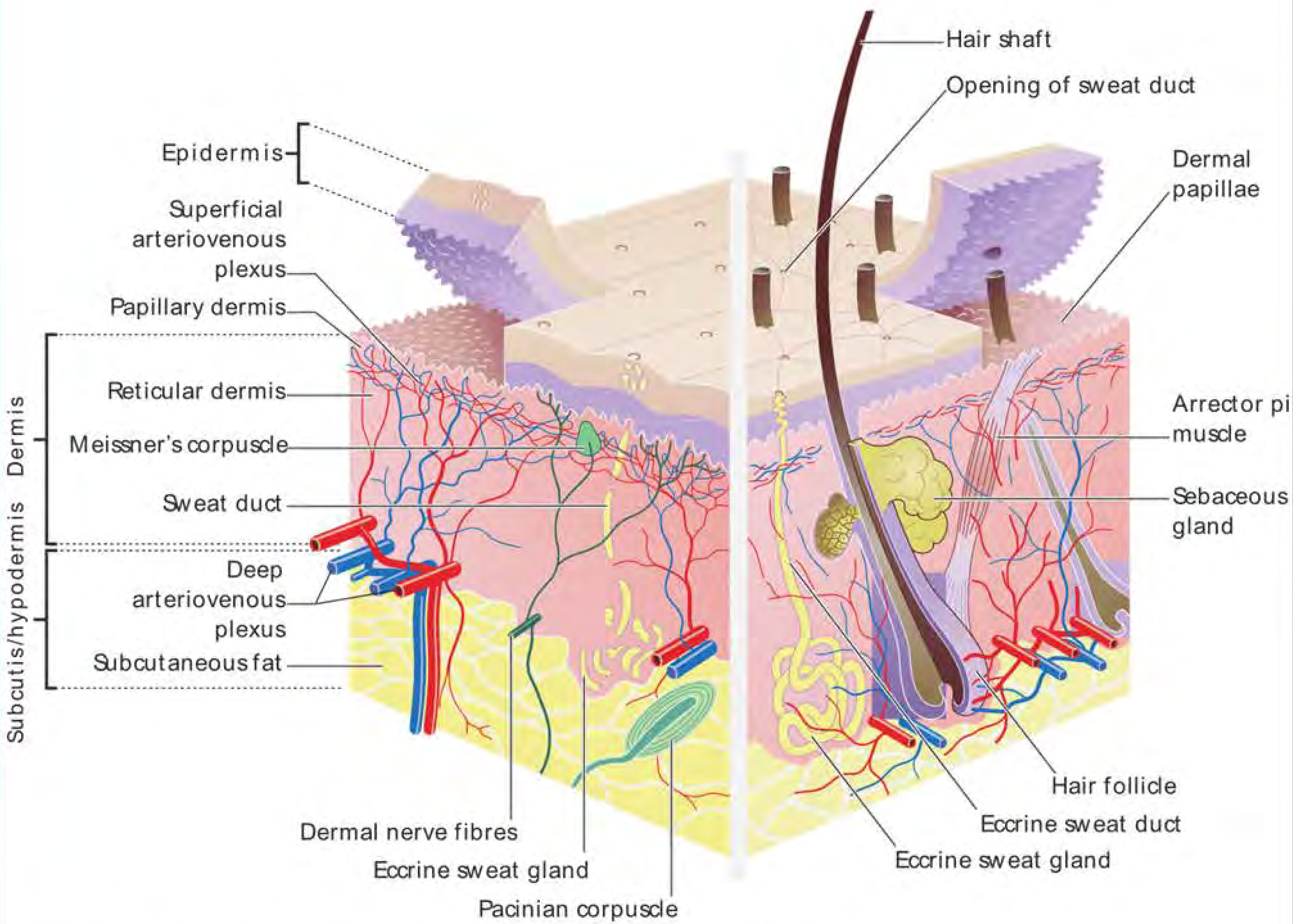
advanced **a**utomotive **m**anikin

human thermal physiological model

the sensitive type


photo credit/source: measuring instruments nw / and the national renewable energy laboratory

thermoreceptors: temperature change



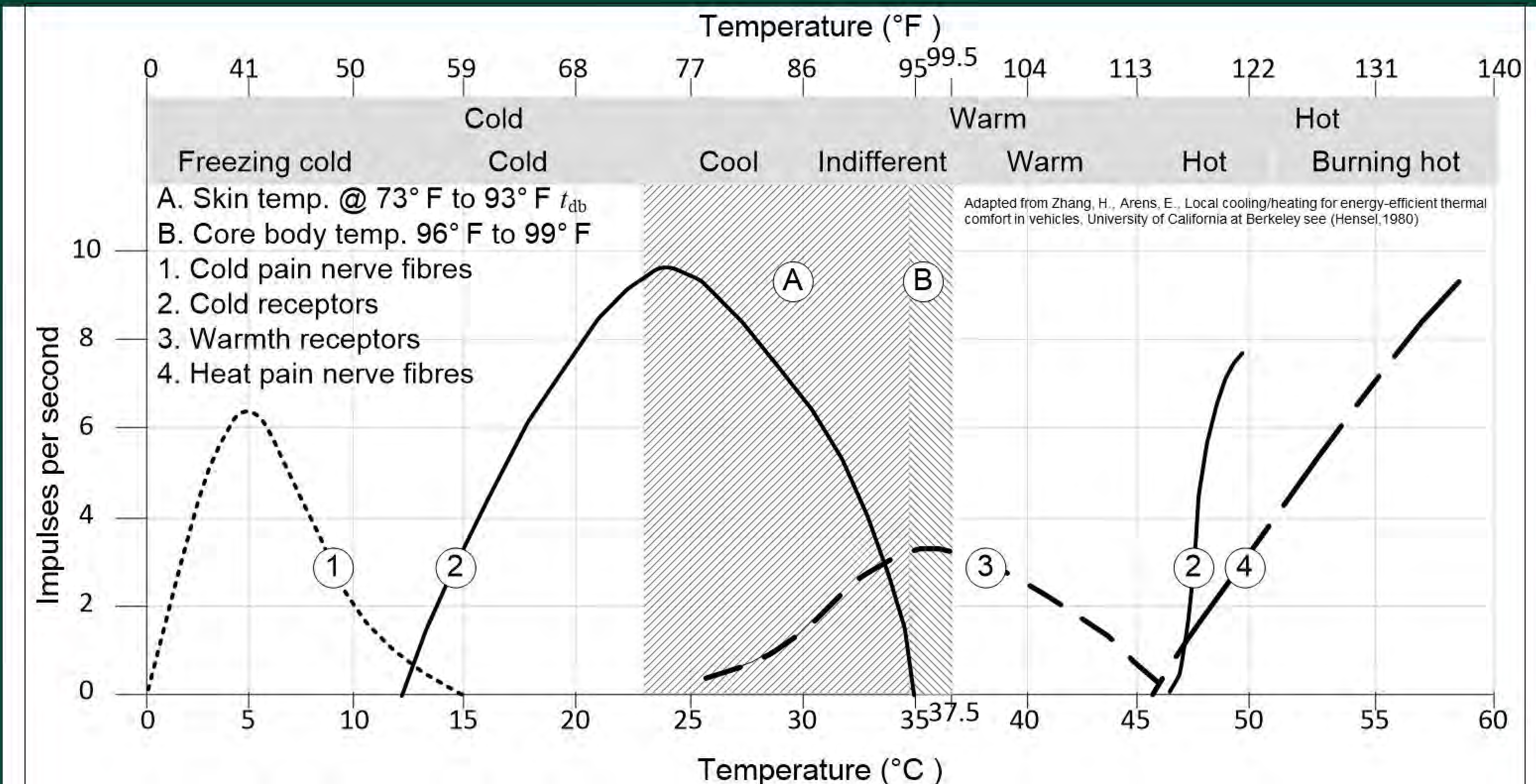
free nerve endings - thermoreceptors

≈150,000 sensitive to heat loss.

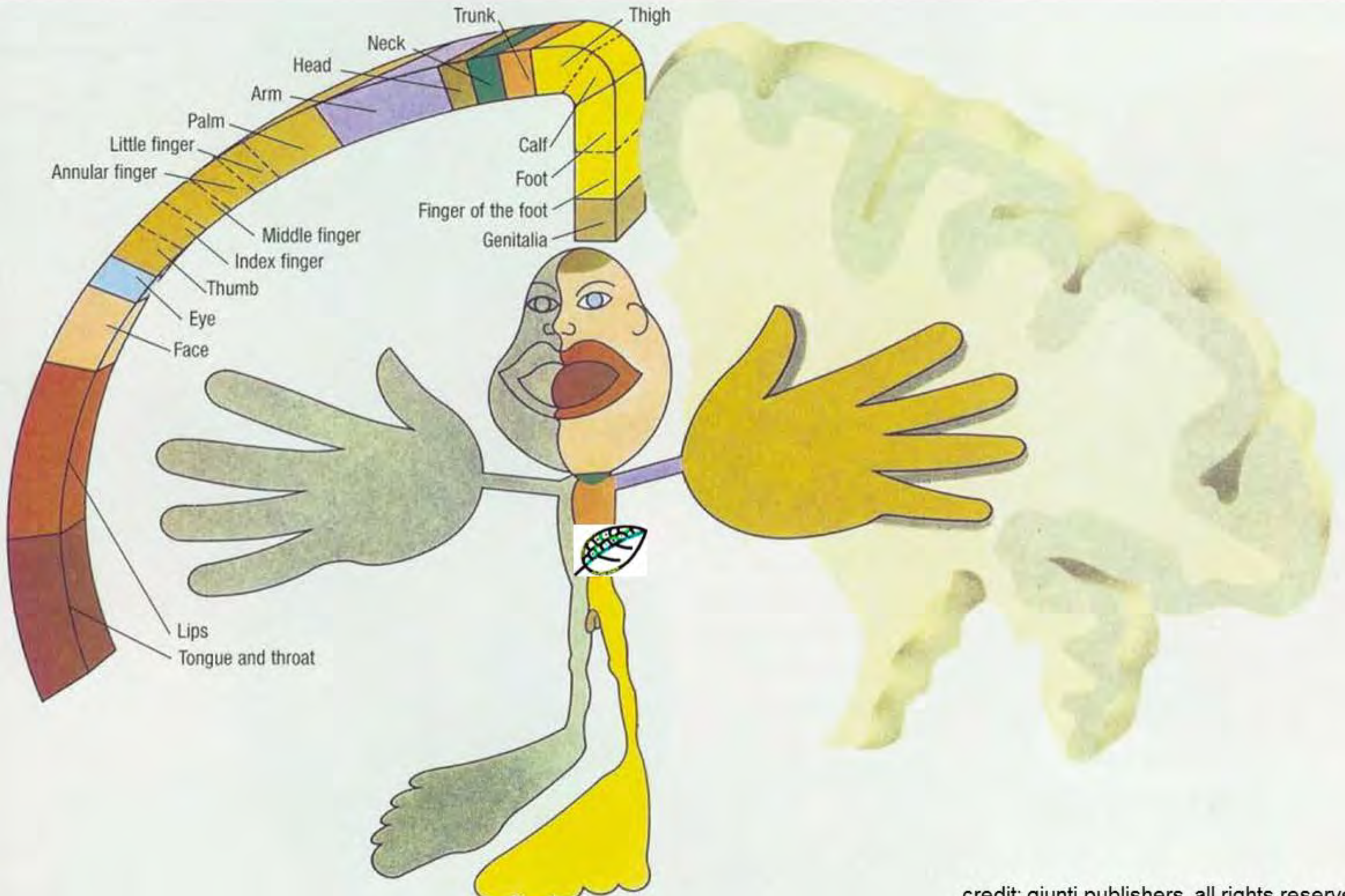
≈16,000 sensitive to heat gain

A. Marsh, Ph.D.

thermoreceptors: temperature change

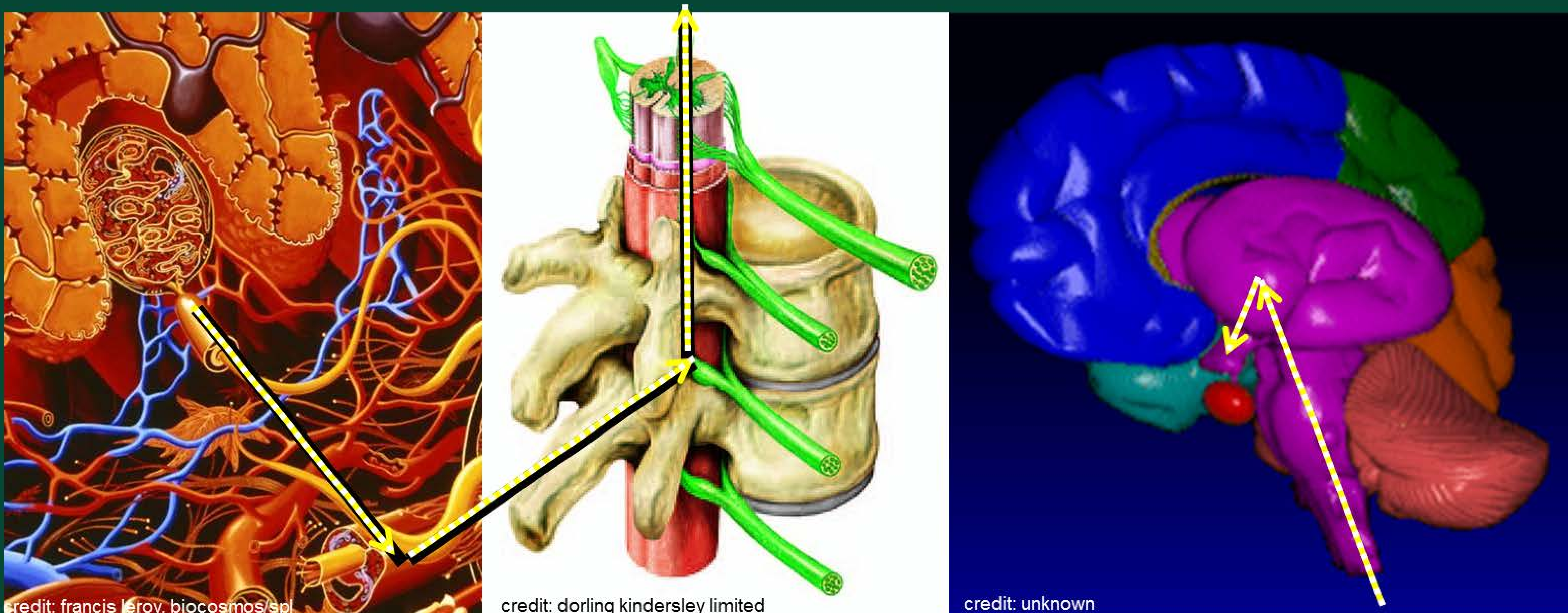


thermoreceptors: temperature change



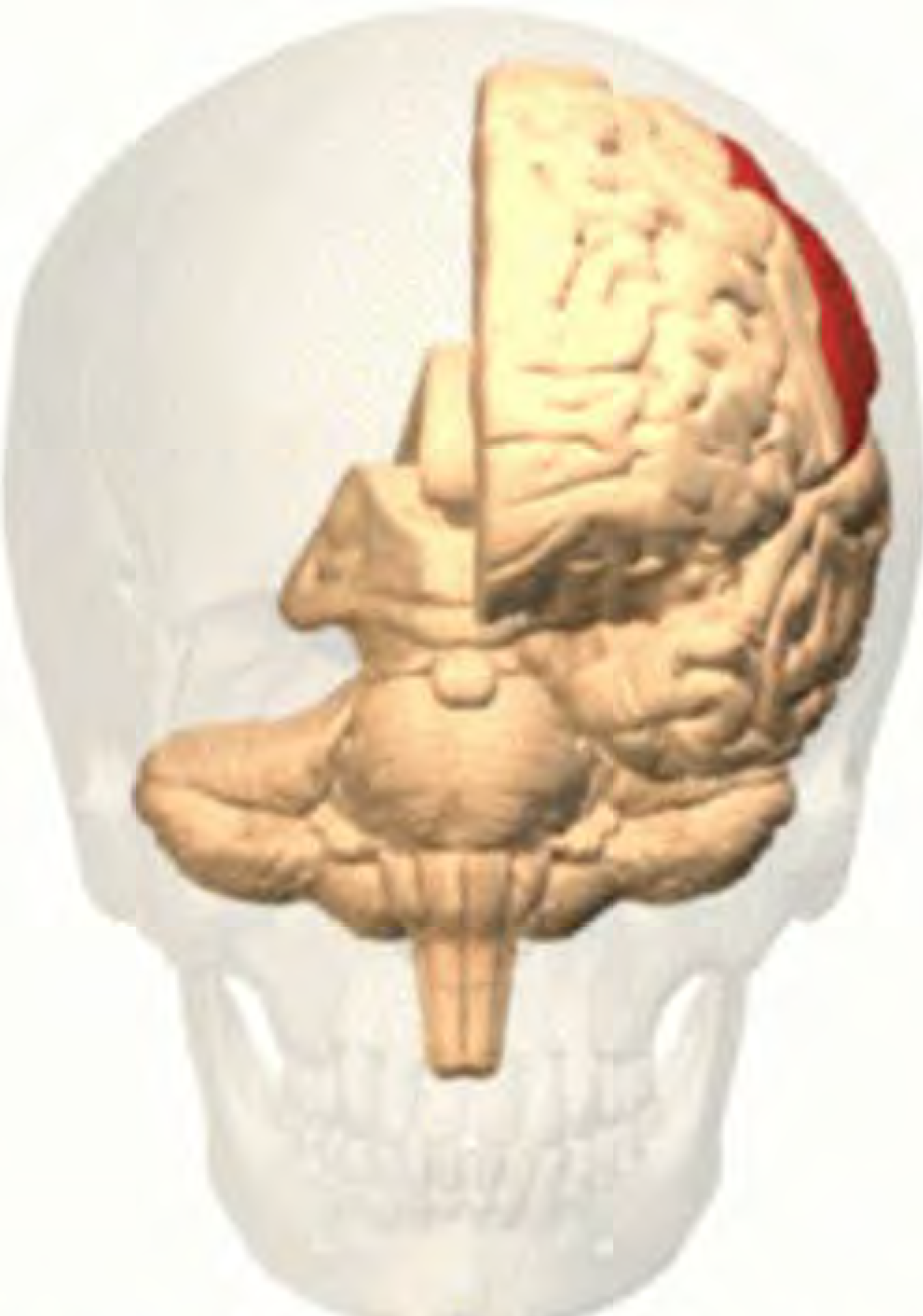
central nervous system

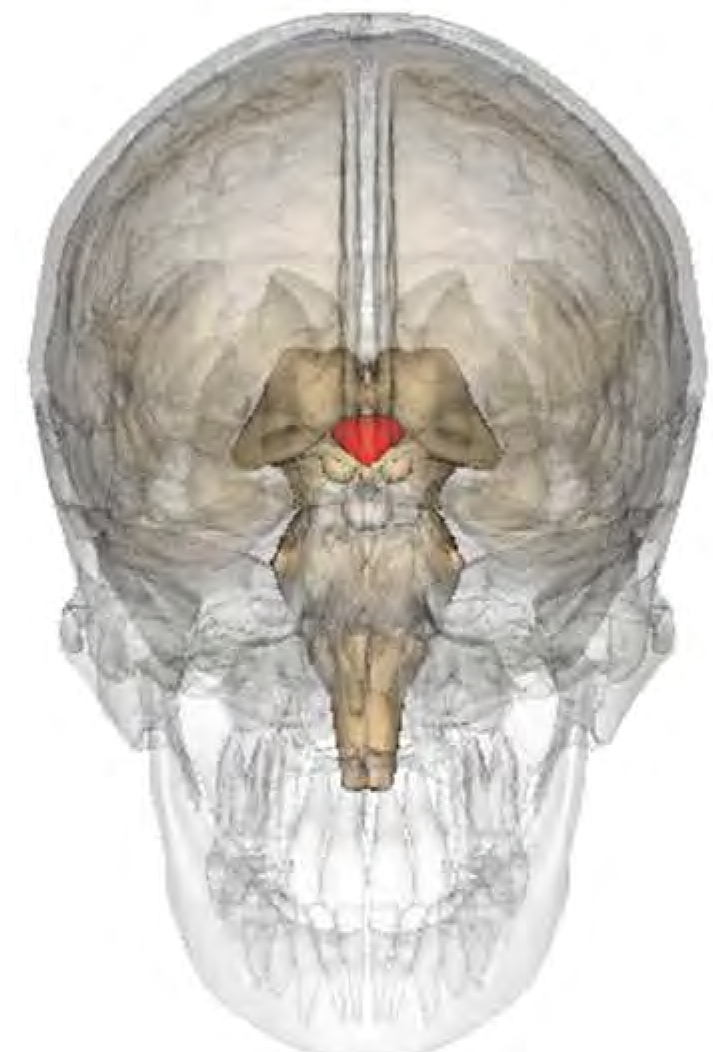
central nervous system



sensors | nerves | thalamus and hypothalamus

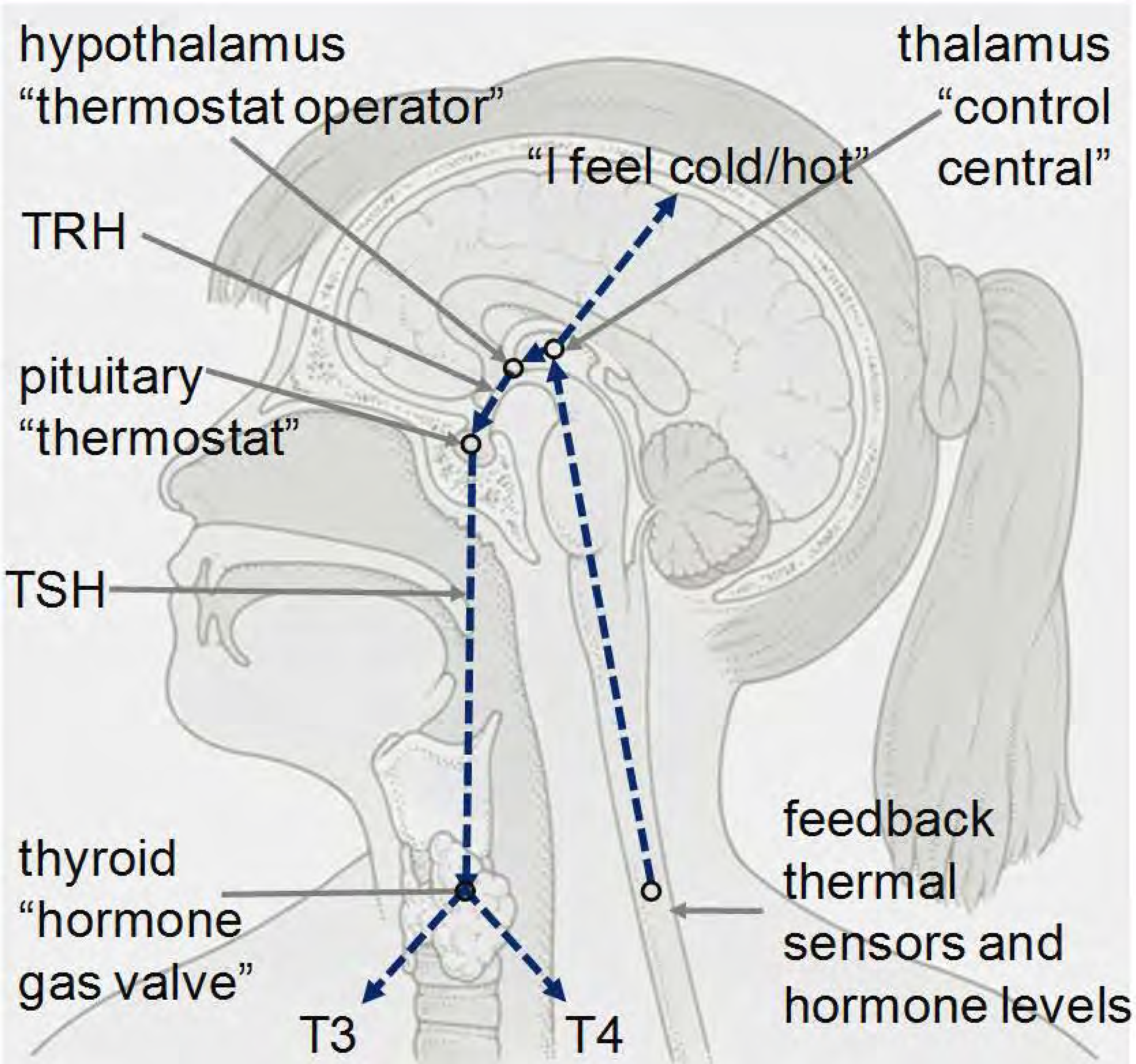
central nervous system





state of mind

comfort:
state of mind
endocrine/autonomic nervous systems



thermal and stress response
neurotransmitters/
hormones
T3, T4
epinephrine,
norepinephrine
cortisol
vis a vis
hypothalamus TRH/CRH
& pituitary TSH/ACTH
thyroid/adrenal gland

thermal regulation

constant core temperature

≈ 96.8°f (sleep) to ≈ 98.2°f (awake)

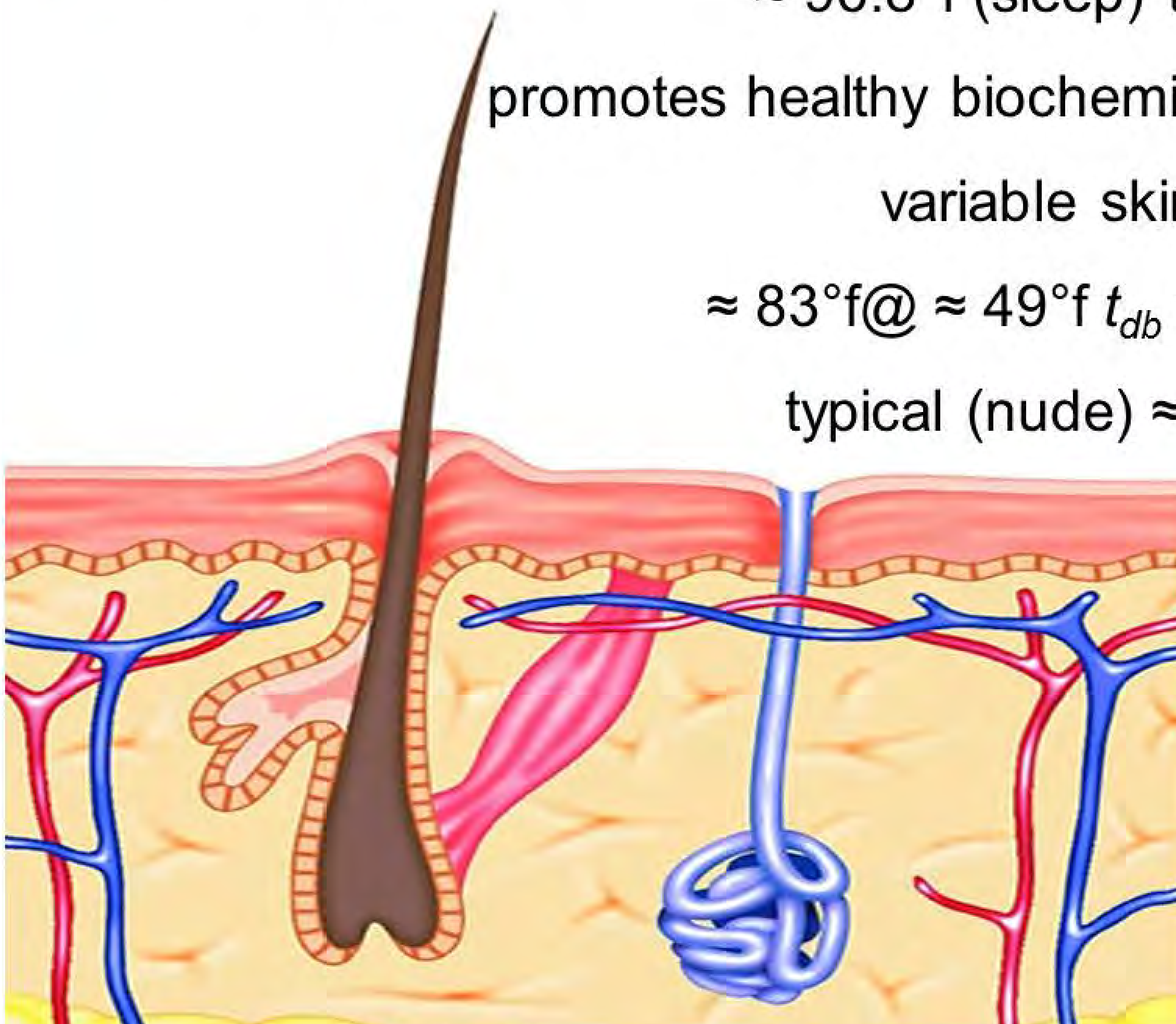
promotes healthy biochemical reactions inside the body

variable skin temperature

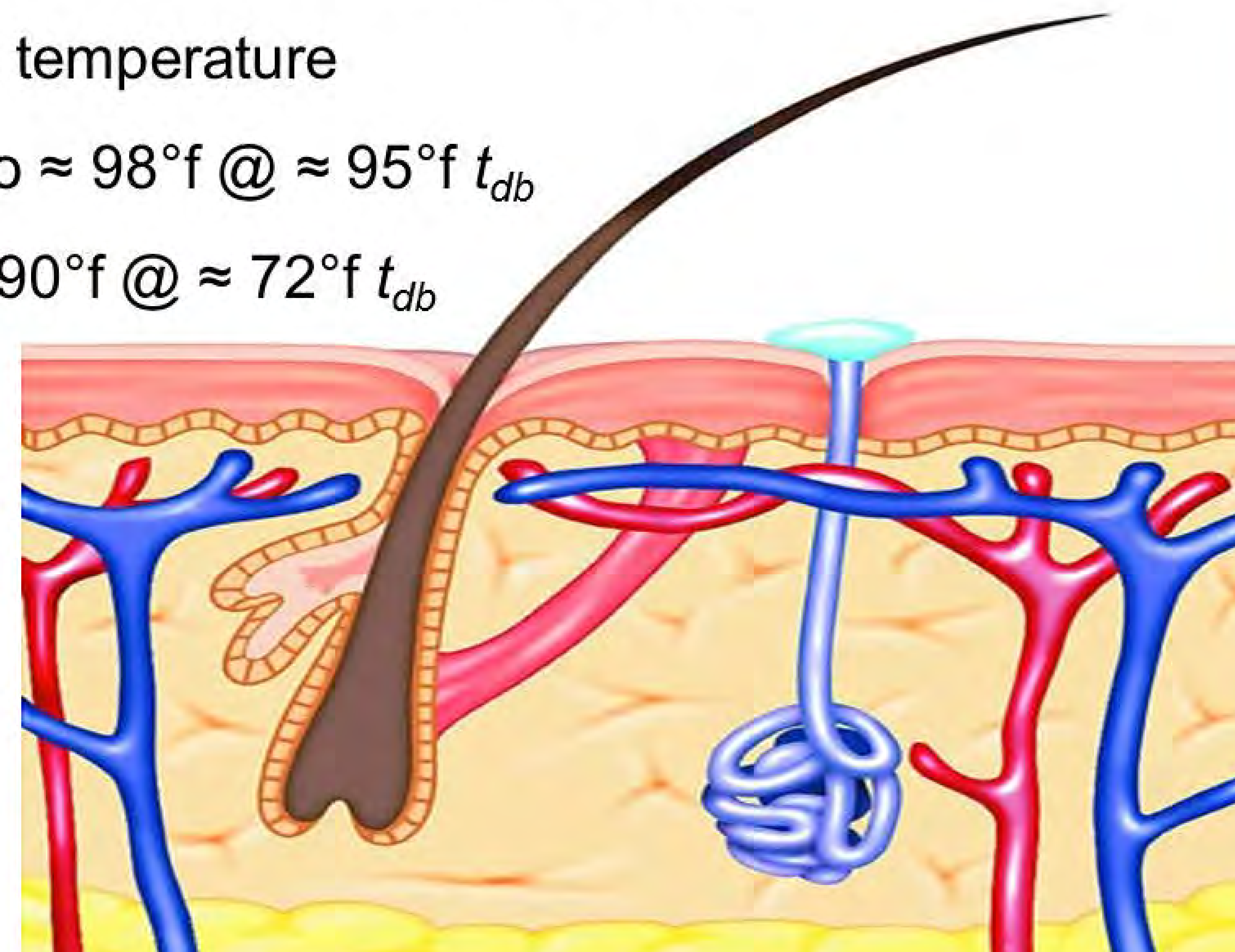
≈ 83°f@ ≈ 49°f t_{db} to ≈ 98°f @ ≈ 95°f t_{db}

typical (nude) ≈ 90°f @ ≈ 72°f t_{db}

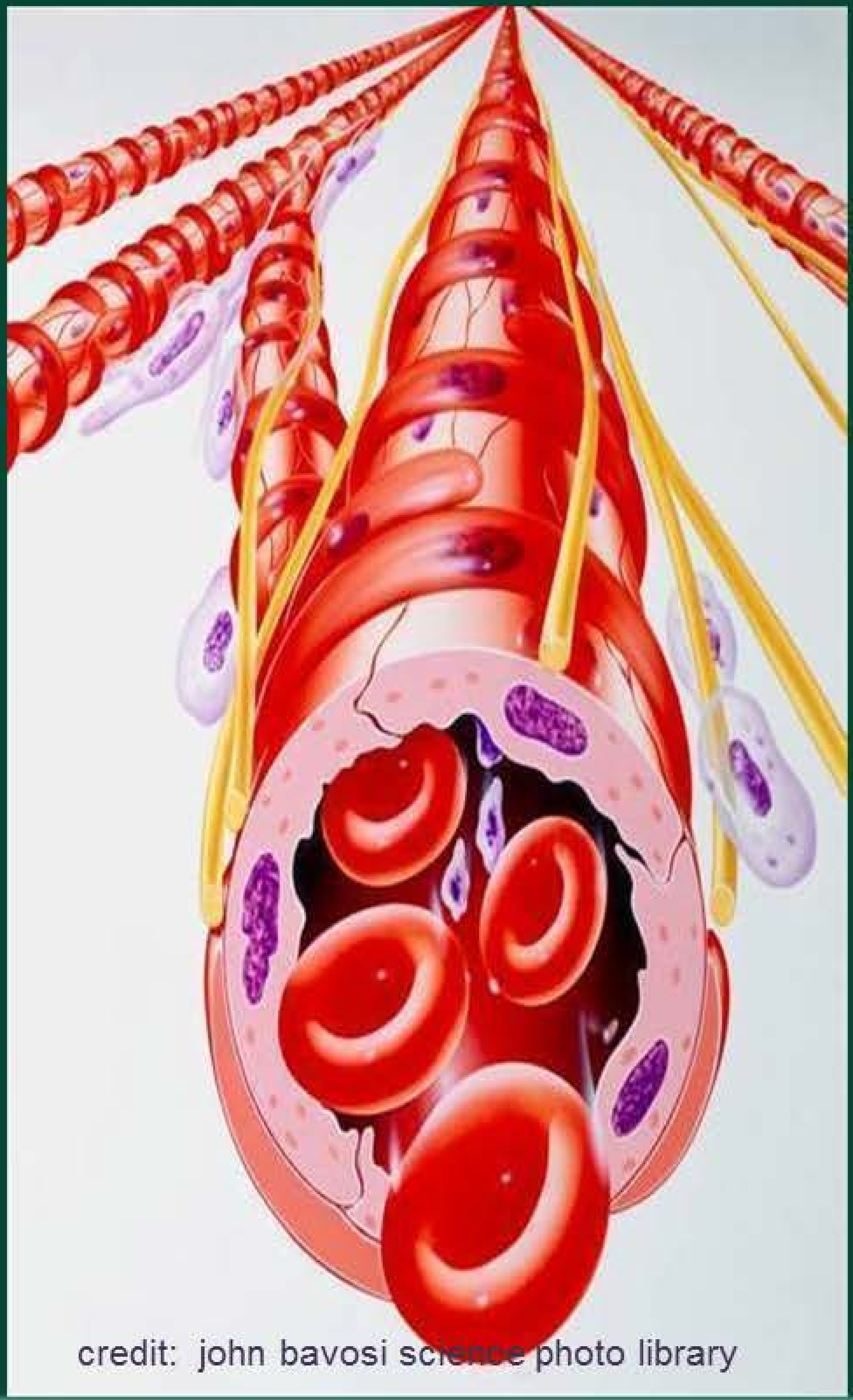
vasoconstriction

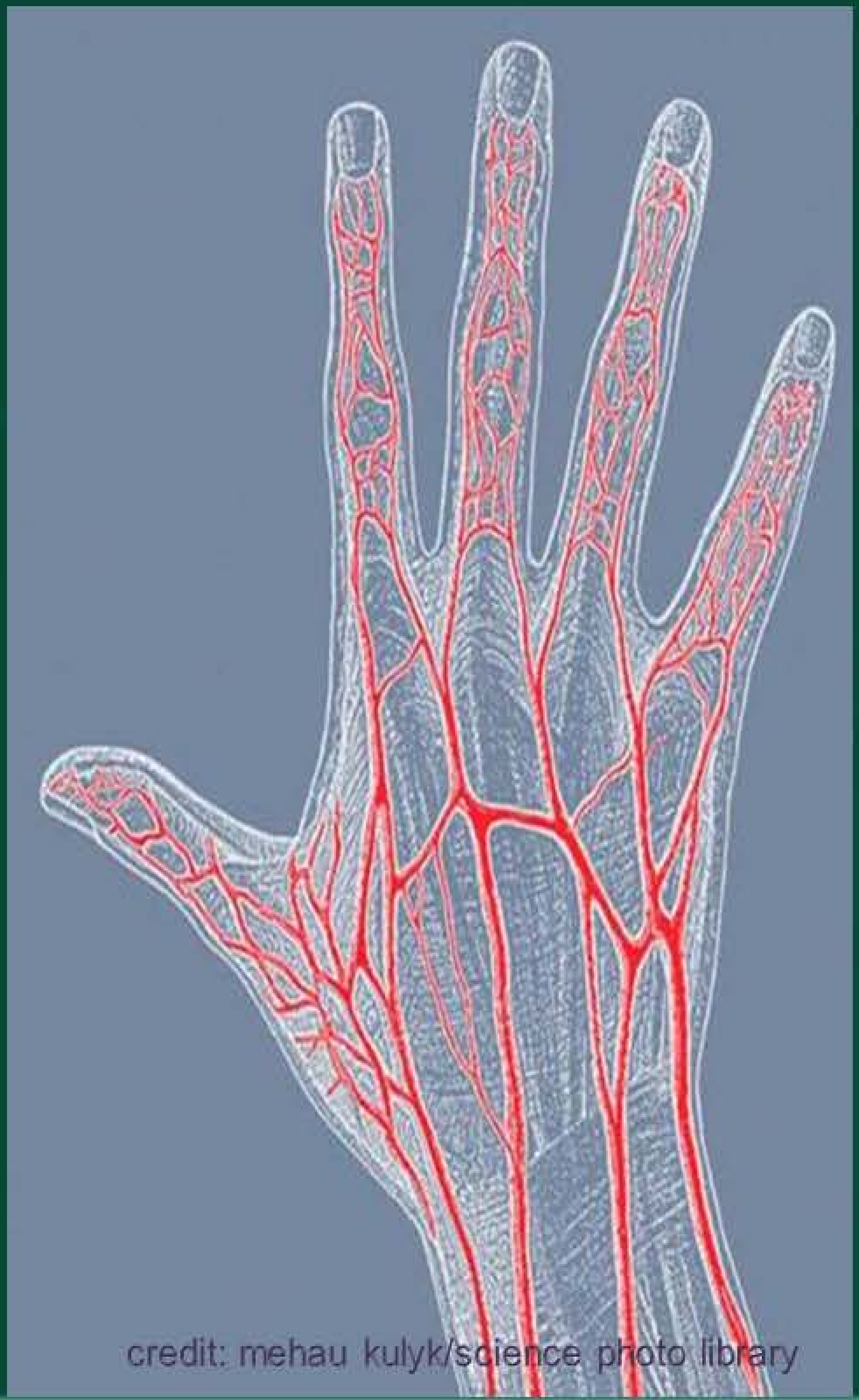


vasodilation



thermal regulation


credit: john bavosi science photo library


credit: mehau kulyk/science photo library

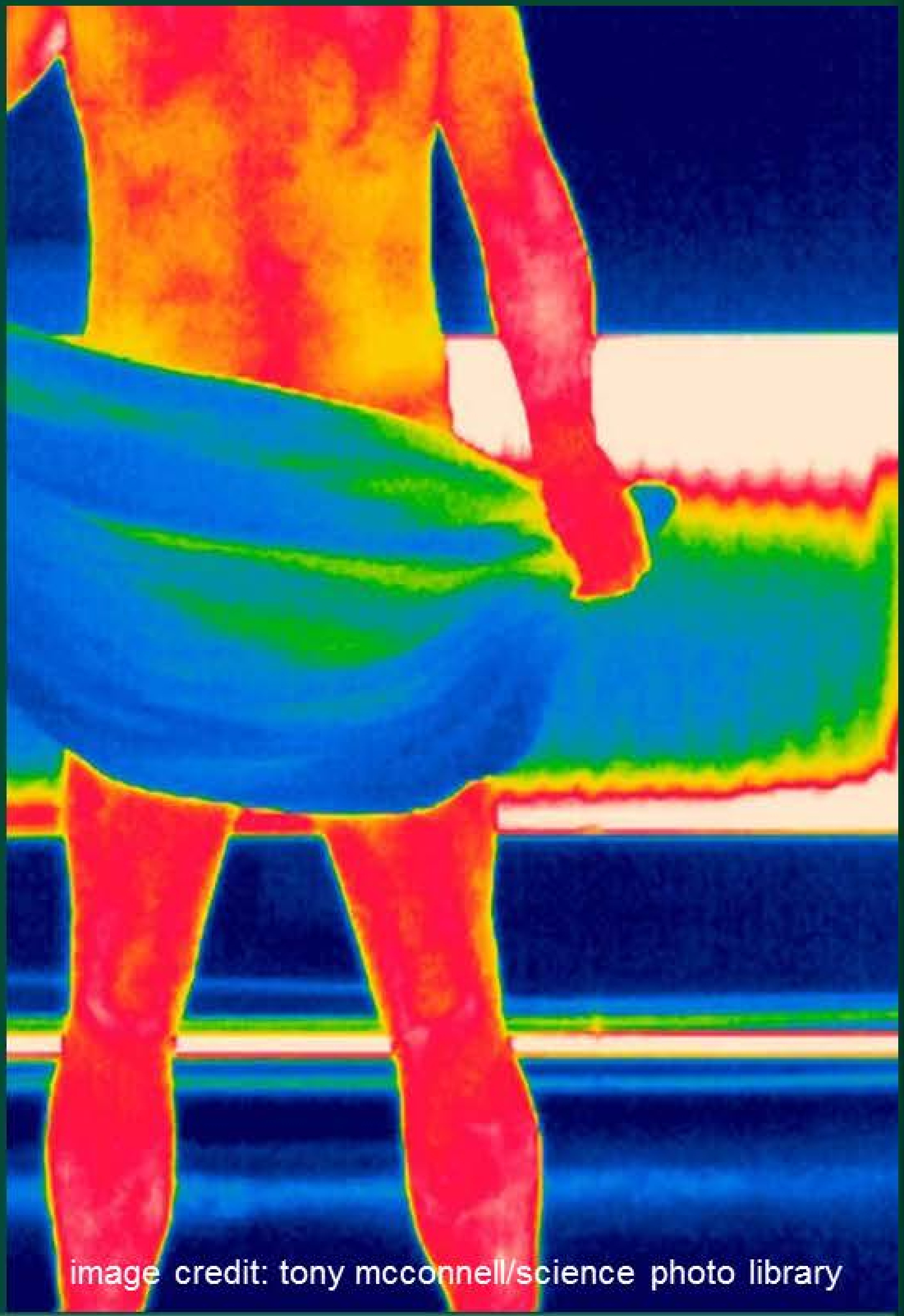


image credit: tony mcconnell/science photo library

building performance - perturbing factors

perturbing factor
high mrt due to solar heat gains

building science
fenestration / env. performance

stimulus
body temp. rises

stimulus
body temp. drops

sensed / transmitted
heat/cool thermoreceptors

received / integrated
thalamus hypothalamus

response
body temp. falls

effector
blood vessels dilate
skin temp rises
glands release sweat

perception / cortex
conscious thought / adaptive

effector
blood vessels constrict
skin temp drops
skeletal muscles shiver

response
body temp. rises

perturbing factor
low mrt due to cold surfaces

building science
fenestration / env. performance

thermal regulation vs indices

environmental indices (resource: 2009 ashrae handbook – fundamentals, chpt 9, thermal comfort)

temperature type	symbol	air	radiant	velocity	humidity
air or dry bulb (99.9% of all thermostats)	t_a or t_{db}	☺	-	-	-
wet bulb globe (exposed to solar but t_a is shaded)	WBGT	☺	☺	☺	☺
equivalent or black globe	t_{eq} or t_g	☺	☺	☺	-
mean radiant	MRT or t_{mr}	-	☺	-	-
operative (abscissa on ASHRAE Std 55 psych chart)	t_o	☺	☺	-	-
humid operative (defined at @100% rh and 0% rh)	t_{oh}	☺	☺	-	☺
effective (defined at @ 50%rh, assumed calm environment, skin wettedness & permeability index specified)	ET*	☺	☺	-	☺
standard effective (50% RH, <0.1 m/s air speed, and tr = ta, 1.0 met and a clothing level of 0.6 clo)	SET*	assumes $t_a = t_{mr}$		☺	☺

direct energy > 6,000,000 customers says…

until the radiant, humidity, velocity problems are solved…

air based

thermostat

remain

dysfunctional

ambassadors

to the

hvac system

illustration credit: (c) steve sweny, all rights reserved, displayed with permission

thermal stressors: a personal story

thermal stressors: a personal story

me to the ICU

doc…your lung

machine isn't

working…

IT SEEMS LIKE THE INTAK VALVE ON THE PUMP IS STICKING

IT HAS BEEN CLICKING ON/OFF

thermal stressors: a personal story

big concerns…

temperature

and air quality!

also I thought

the intubation

tube was too

deep…just

saying…

reality is…

current artificial hardware is a poor proxy for human software

so why study this stuff?

"….that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation"

ASHRAE Standard 55

a 1966 thermal comfort standard replacing the 1938 code of minimum requirements…someone forgot to tell the building industry!

THERMAL COMFORT CONDITIONS

Effective January 27, 1966

AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING
UNITED ENGINEERING CENTER, 345 EAST 47th STREET, NEW YORK, N.

INTRODUCTION

This standard specifies the environmental conditions that will provide year-around thermal comfort for most people, normally clothed, engaged in sedentary or near sedentary activities. The limits on the specifications have been based on the current state of knowledge of environmental physiology, comfort research and commercial practice. This standard replaces the Code of Minimum Requirements for Comfort Air Conditioning (1938).

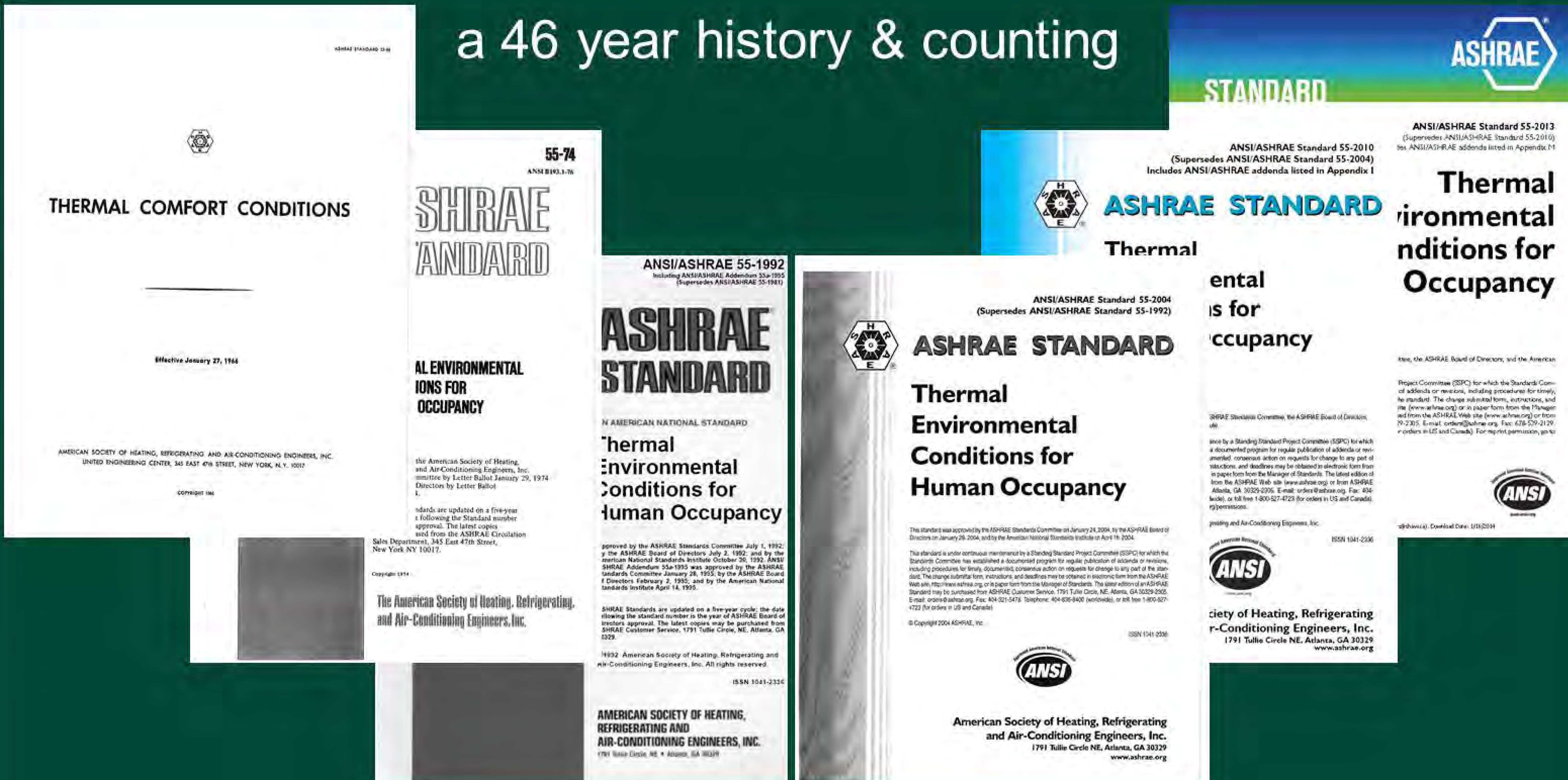
Section 1.0 Purpose and Scope

1.1 This standard specifies desirable and generally acceptable thermal environmental conditions for comfort of sedentary and slightly active, healthy and normally clothed people in the United States and Canada.

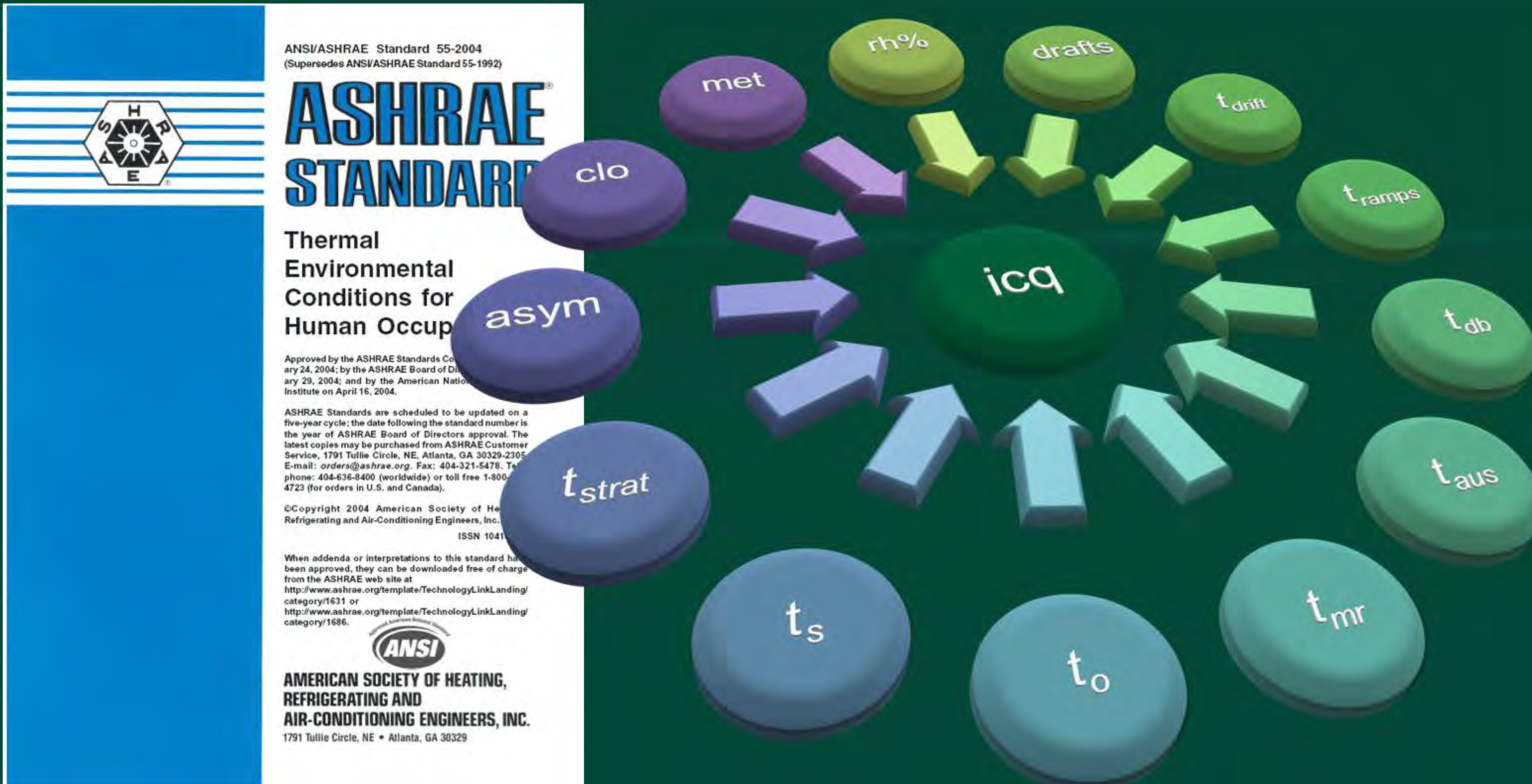
1.2 This standard does not specify the non-thermal environmental factors such as ventilation rates, noise, illumination, etc.

ASHRAE Standard 55

a 46 year history & counting



ASHRAE Standard 55



ASHRAE Standard 55

factors affecting thermal comfort (* strictly influenced by enclosure performance; dry bulb & rh is co-influenced by enclosures exclusively conditioned with air based hvac systems.)	
general environmental factors	**localized factors**
dry bulb temperature	vertical air temperature differences*
mean radiant temperature*	radiant temperature asymmetry*
humidity	floor temperature*
air speed	drafts*
personal factors	
metabolic rate	clothing

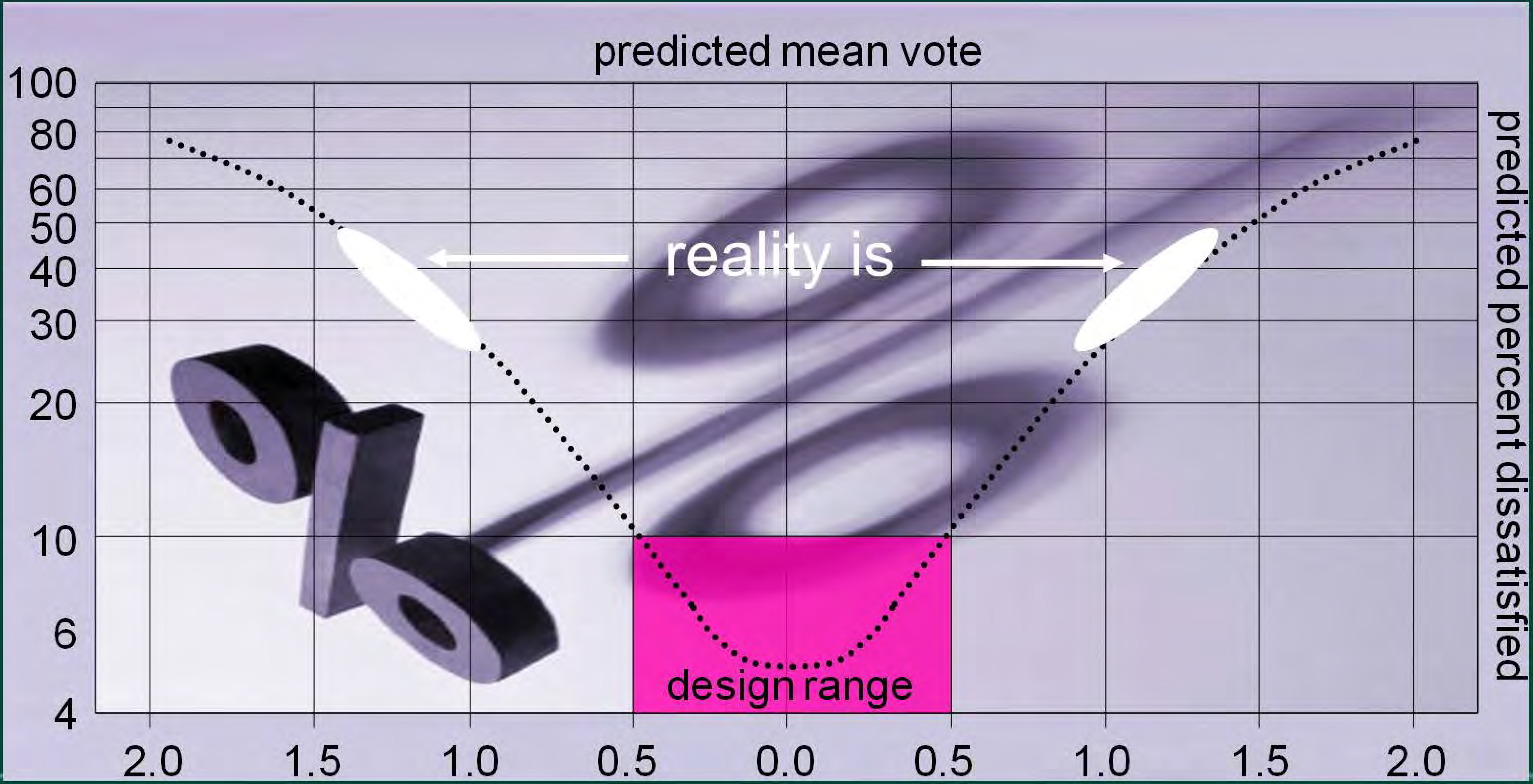
source/credit: ansi/ashrae standard 55 - thermal environmental conditions for human occupancy

ASHRAE Standard 55

cold	mind neutral	hot
hypothermia		hyperthermia
blood flows to internal organs		blood flows outward to skin
shiver		sweat
← want warmer →	body neutral	← want cooler →

-3	-2	-1	0	1	2	3
cold	cool	slightly cool		slightly warm	warm	hot

ASHRAE Standard 55

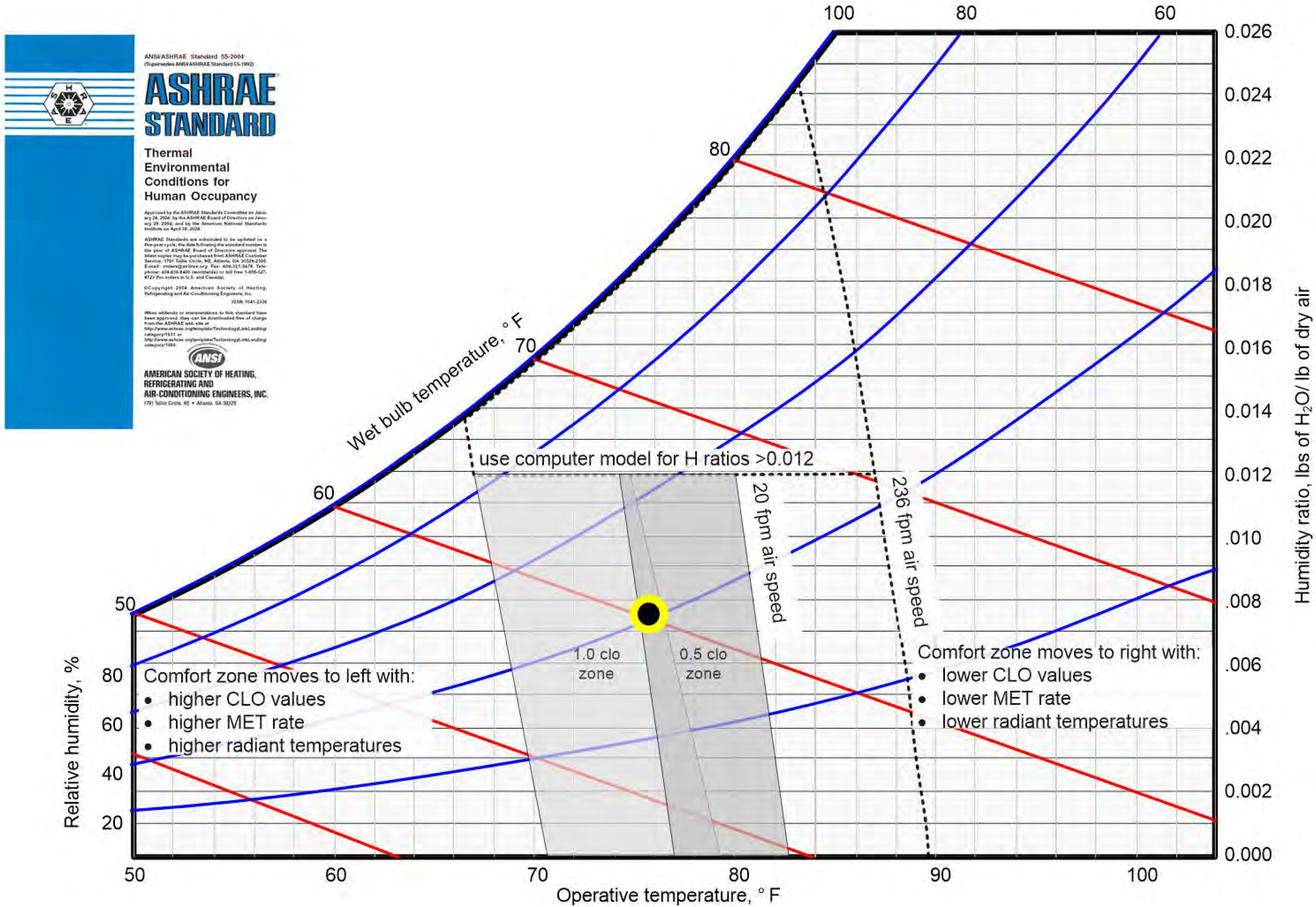


ASHRAE Standard 55

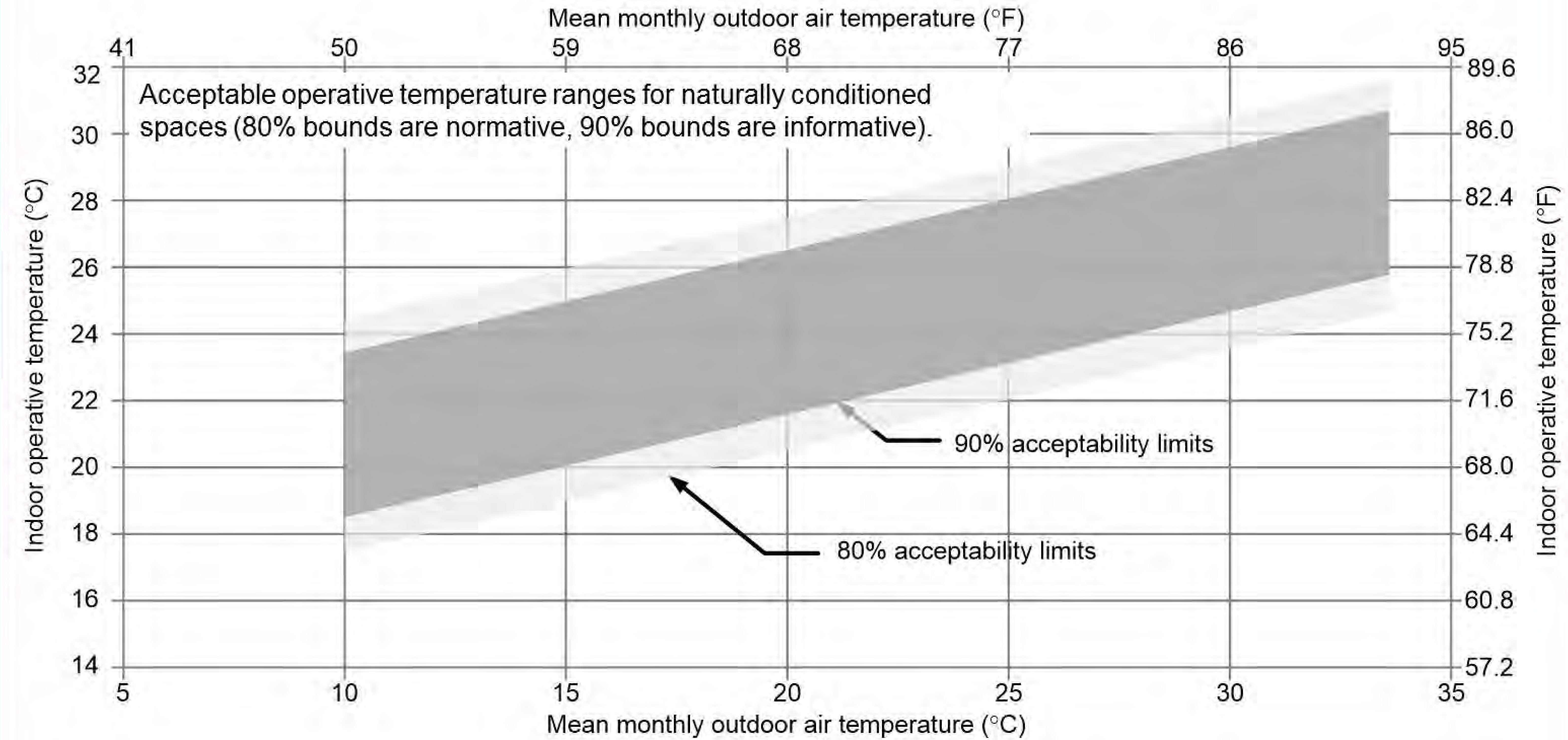
compliance paths

graphical, adaptive or

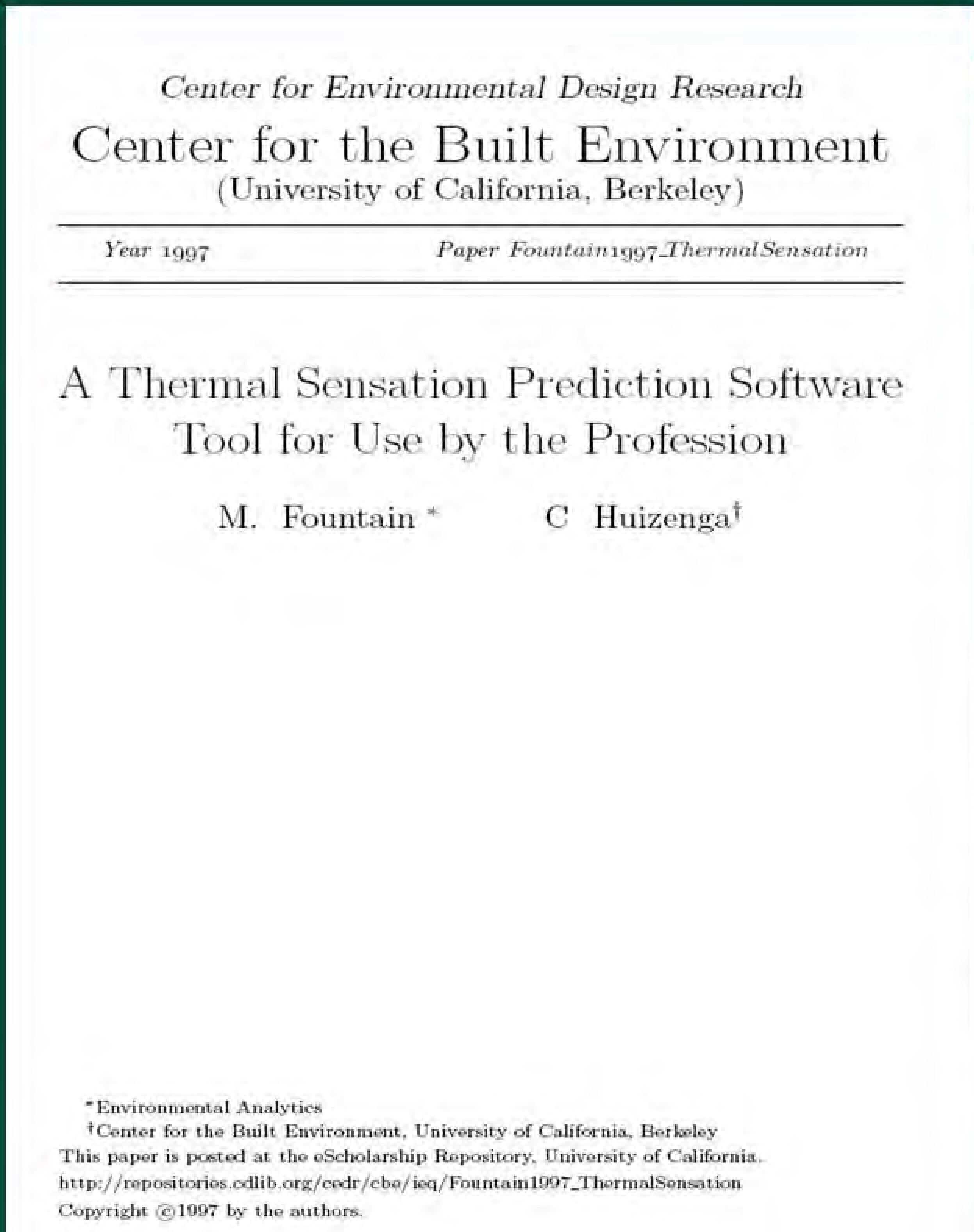
analytical method


ANSI/ASHRAE Standard 55-2004
ASHRAE STANDARD
Thermal Environmental Conditions for Human Occupancy
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
Wet bulb temperature, °F
50
60
70
80
100
80
60
use computer model for H ratios >0.012
20 fpm air speed
236 fpm air speed
1.0 clo zone
0.5 clo zone
Comfort zone moves to left with:
• higher CLO values
• higher MET rate
• higher radiant temperatures
Comfort zone moves to right with:
• lower CLO values
• lower MET rate
• lower radiant temperatures
Relative humidity, %
80
60
40
20
Operative temperature, °F
50
60
70
80
90
100
Humidity ratio, lbs of H2O/ lb of dry air
0.026
0.024
0.022
0.020
0.018
0.016
0.014
0.012
.010
.008
.006
.004
0.002
0.000

ASHRAE Standard 55



ASHRAE Standard 55



Center for Environmental Design Research

Center for the Built Environment

(University of California, Berkeley)

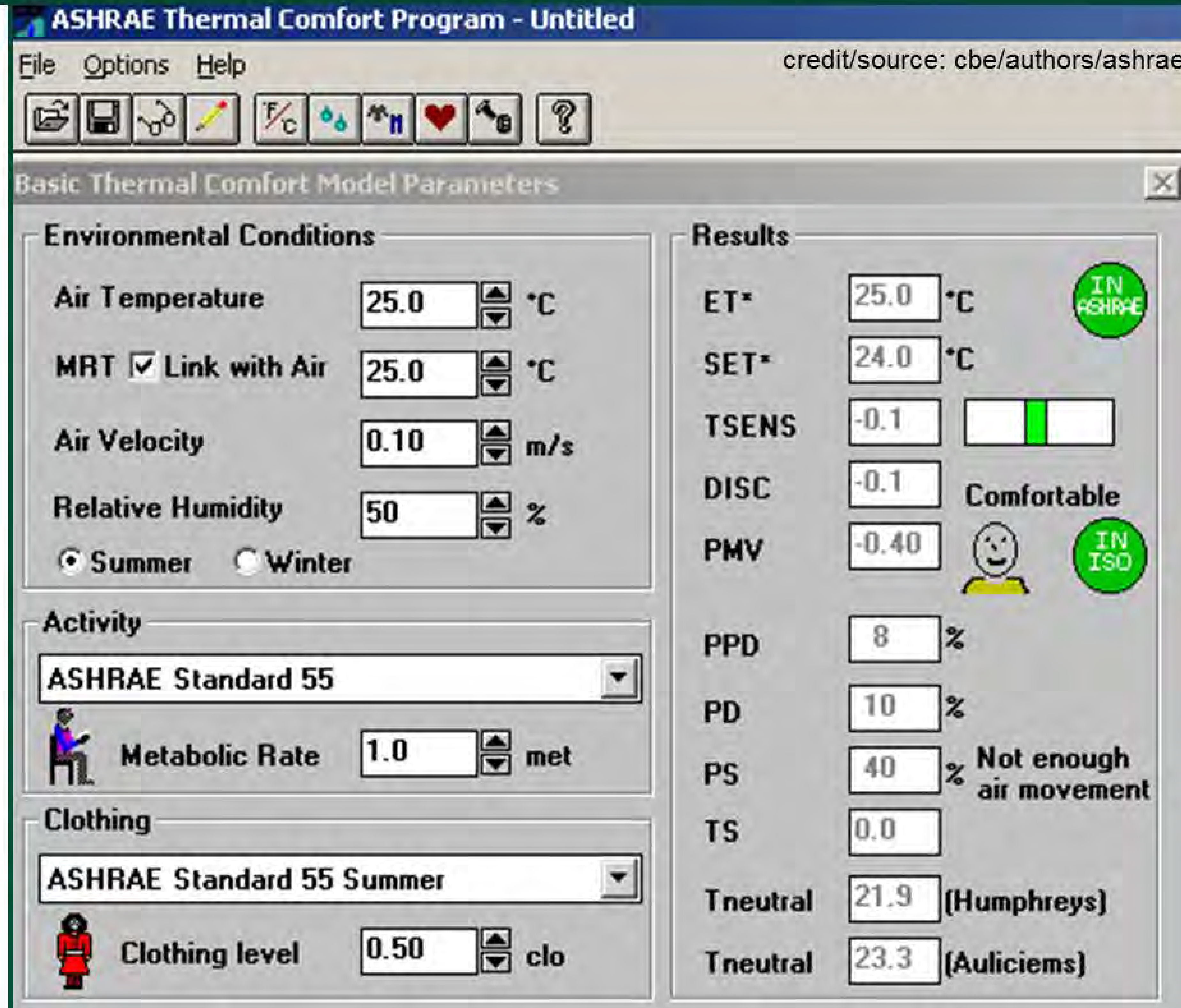
Year 1997 *Paper* Fountain1997_ThermalSensation

A Thermal Sensation Prediction Software Tool for Use by the Profession

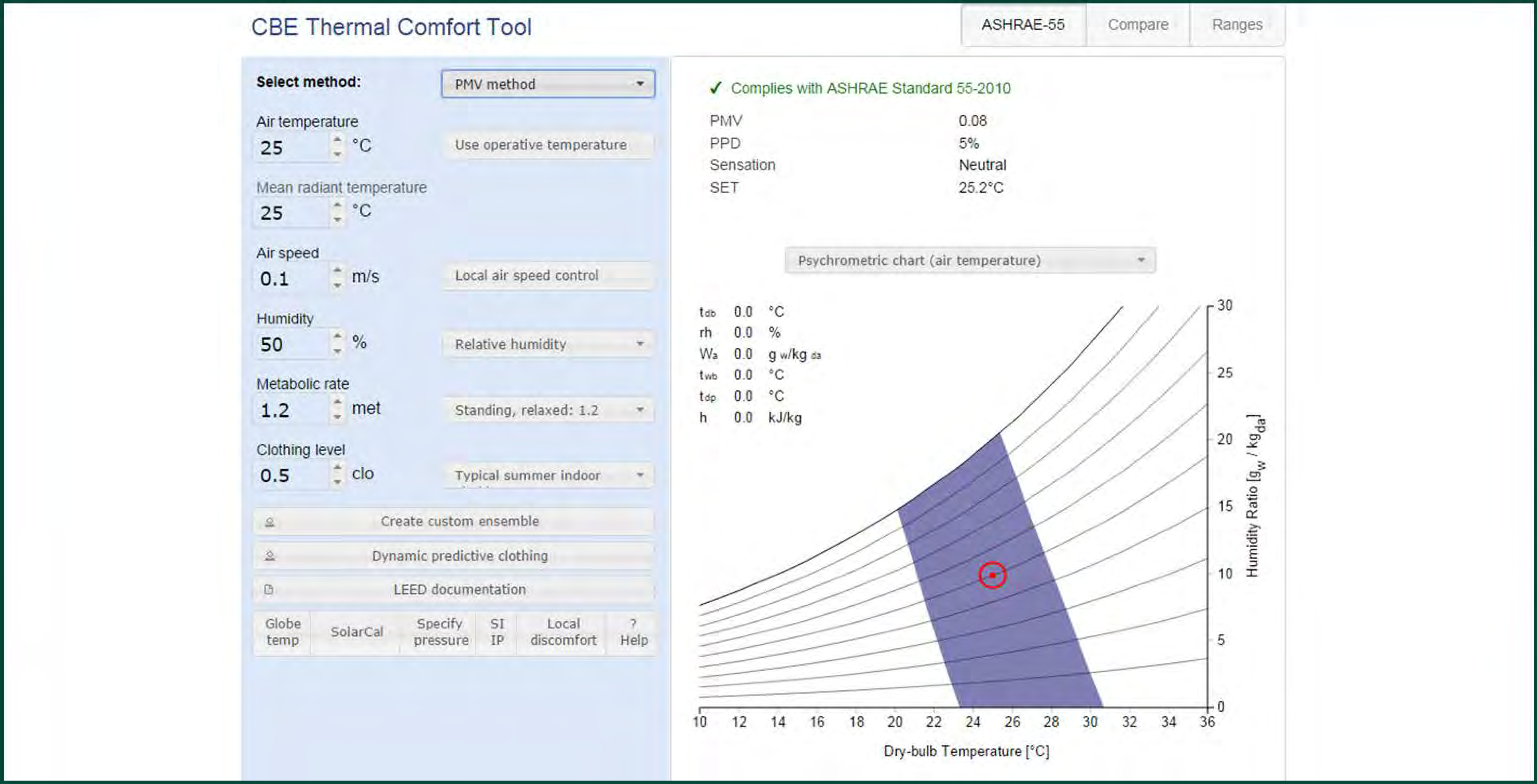
M. Fountain * C Huizenga†

*Environmental Analytics

†Center for the Built Environment, University of California, Berkeley



ASHRAE Standard 55



ASHRAE Standard 55

CBE Thermal Comfort Tool

ASHRAE-55 | Compare | Ranges

Select method: Adaptive method

Air temperature
25 °C
Use operative temperature

Mean radiant temperature
25 °C

Prevailing mean outdoor temperature
29 °C

Air speed
0.3 m/s (59 fpm)

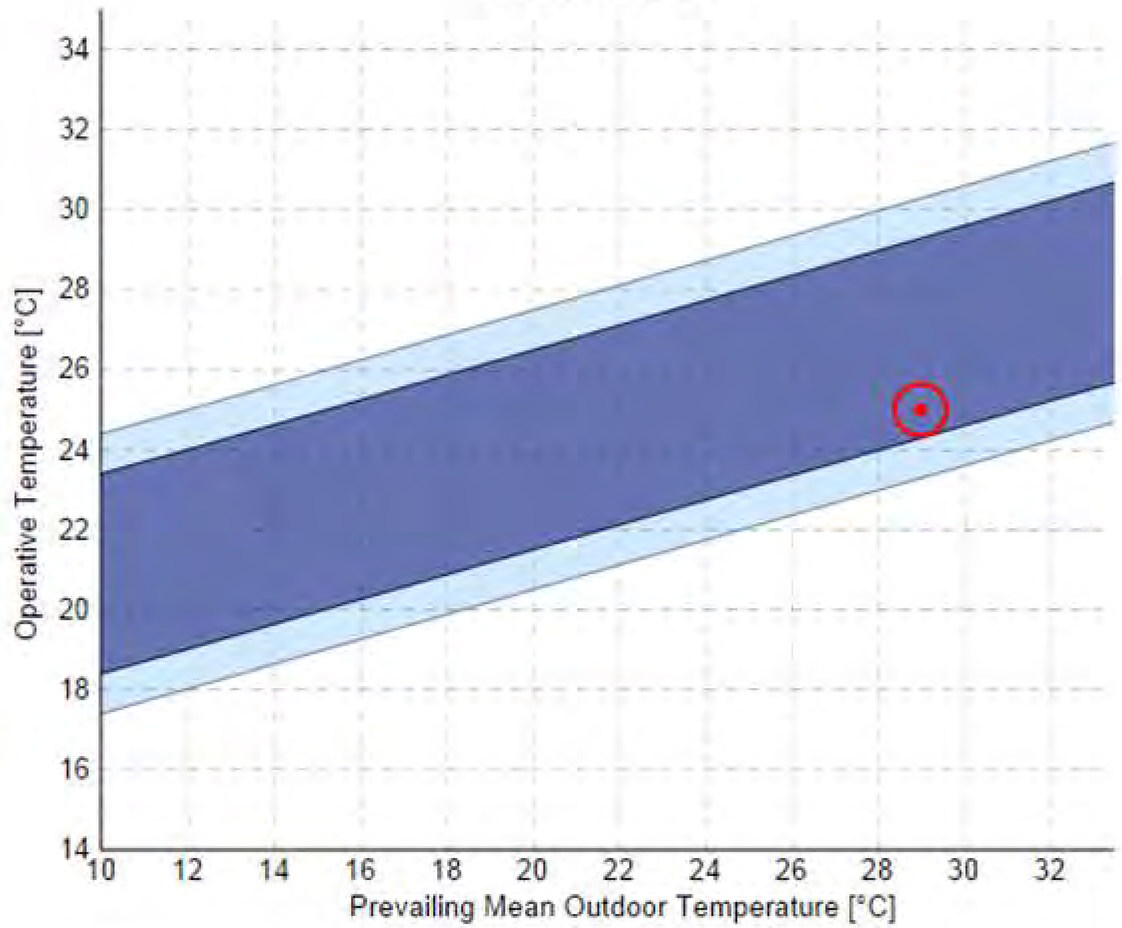
LEED documentation

Globe temp | SolarCal | Specify pressure | SI IP | Local discomfort | ? Help

✓ Complies with ASHRAE Standard 55-2010

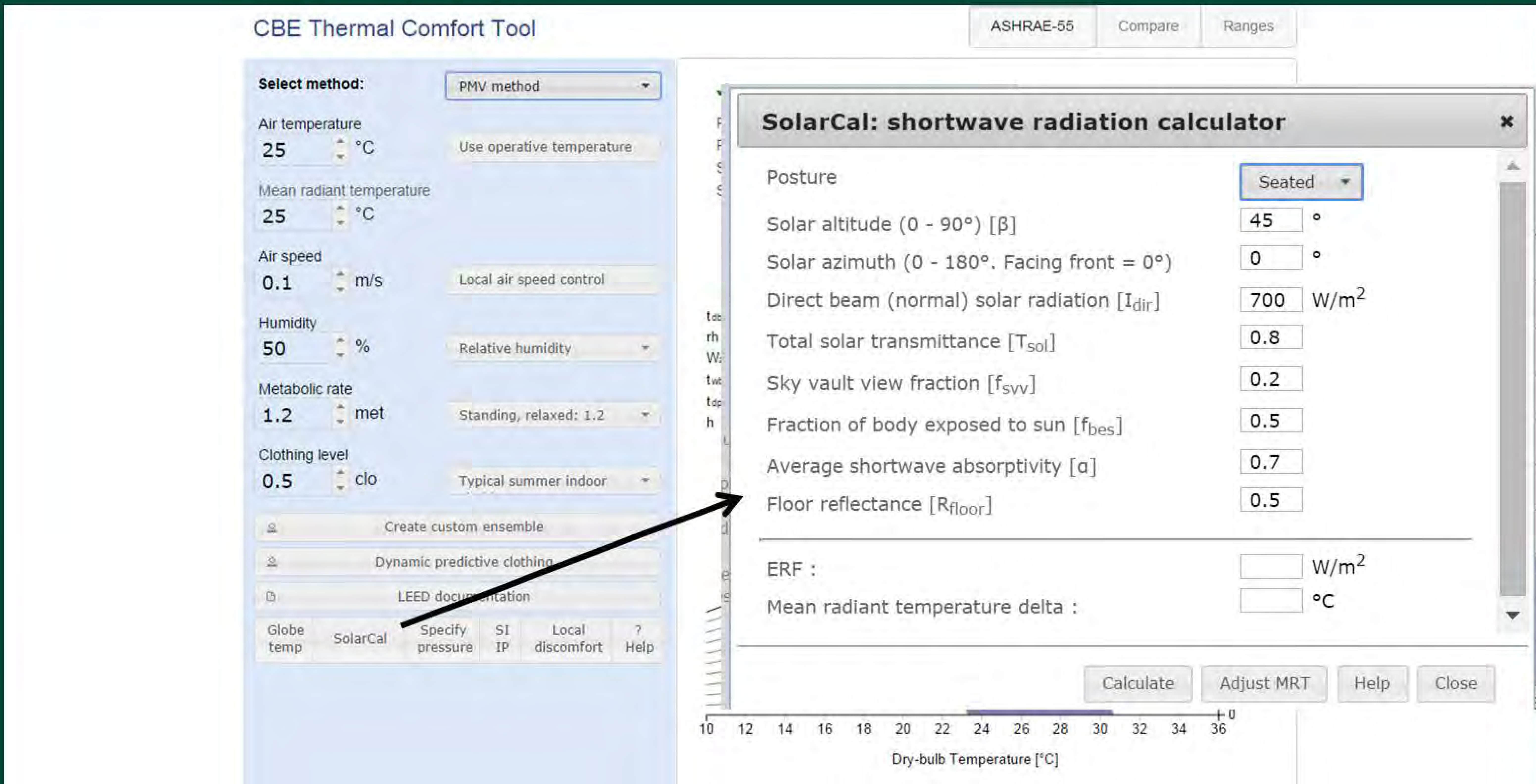
80% acceptability limits	Operative temperature: 23.3 to 30.3°C
└ Status	Comfortable
90% acceptability limits	Operative temperature: 24.3 to 29.3°C
└ Status	Comfortable

Adaptive chart

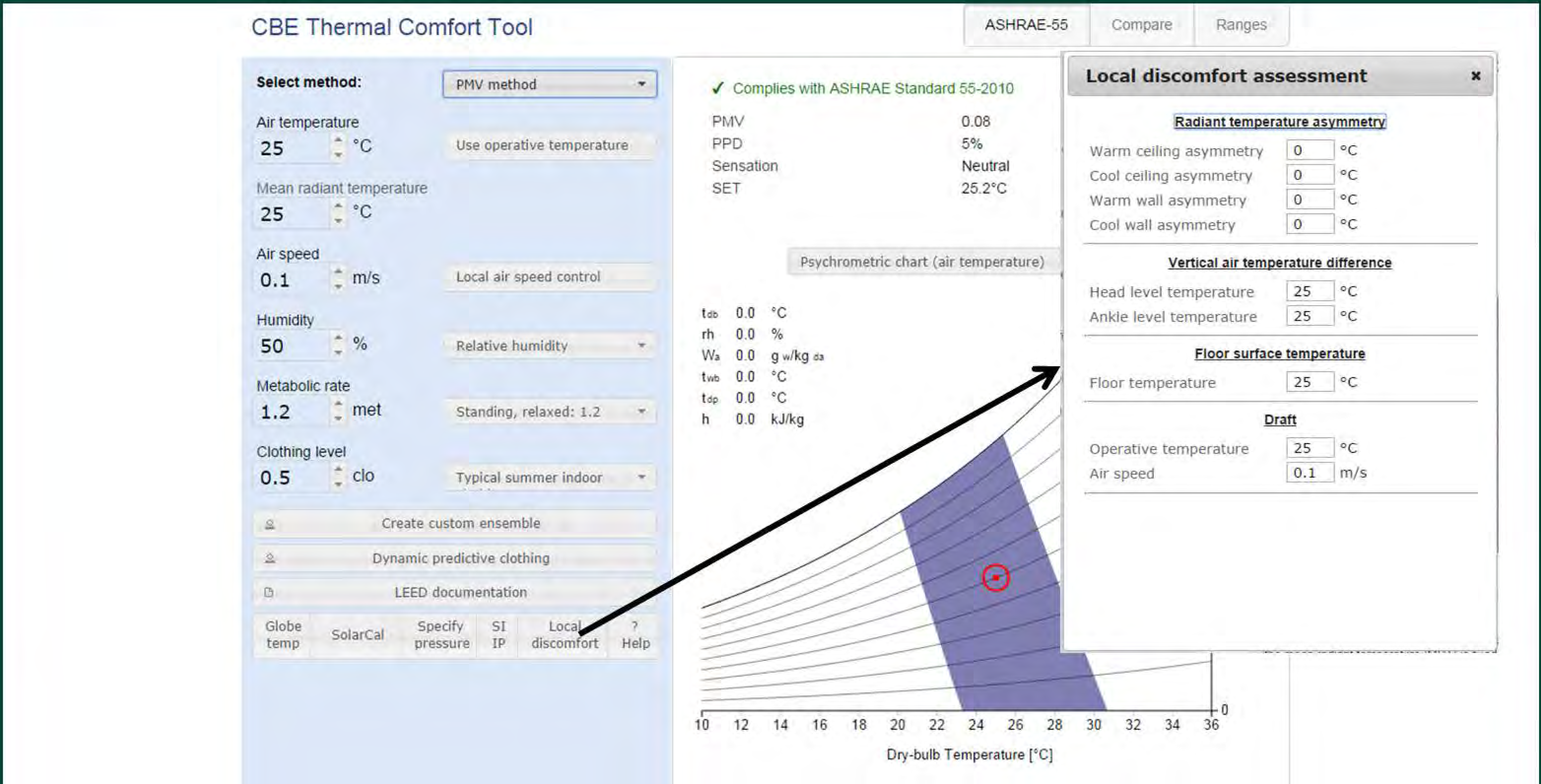


NOTE: Method is applicable only for occupant-controlled naturally conditioned spaces that meet all of the following criteria: (a) There is no mechanical cooling

ASHRAE Standard 55



ASHRAE Standard 55



ASHRAE Standard 55

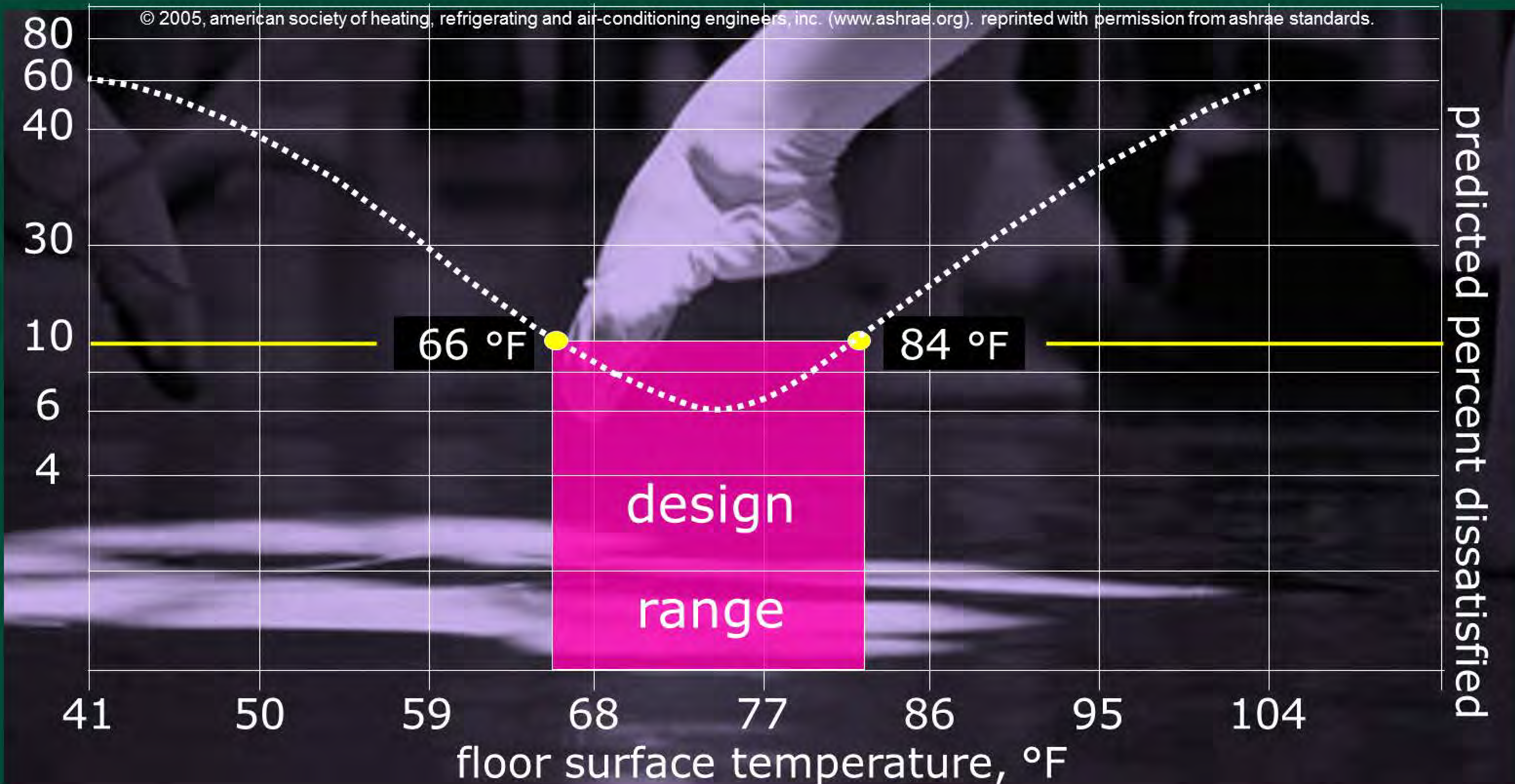
localized discomfort

floor temperature, radiant asymmetry, temperature stratification and drafts

will overshadows general comfort

dry bulb, mean radiant, humidity and air velocity

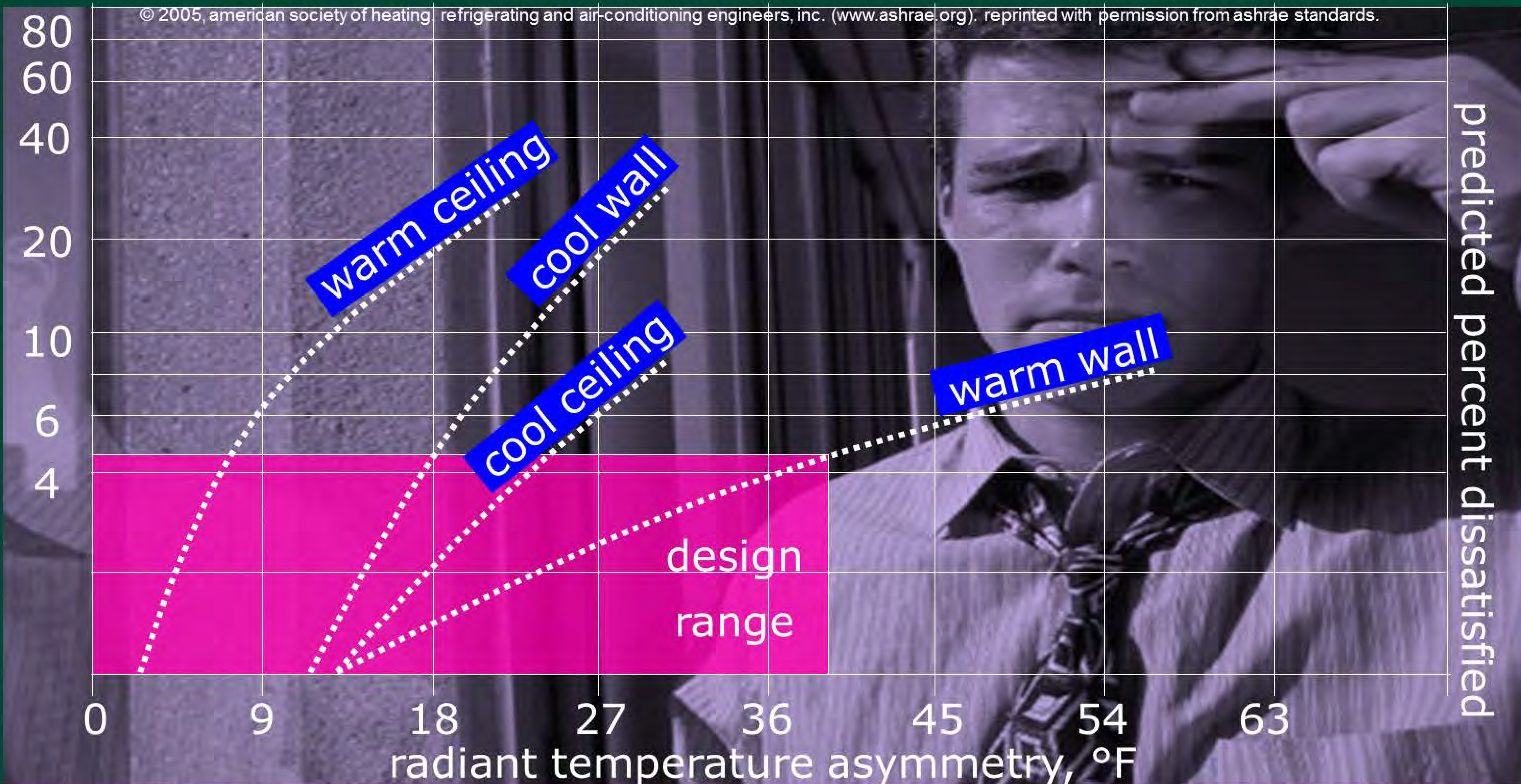
floor surface temperature



floor coverings matter

Contact coefficient for various floor coverings based on conductivity, density and specific heat	
Flooring	Contact coefficient, b (kCal/m2 $hr^{0.5}$ °C)
Steel	180
Concrete	25
Linoleum,	9
Oak wood	7
Pine wood	4
Cork	2
source: Fanger, P.O., Thermal Comfort: Analysis and Applications in Environmental Engineering, McGraw-Hill Book Company, 1970	

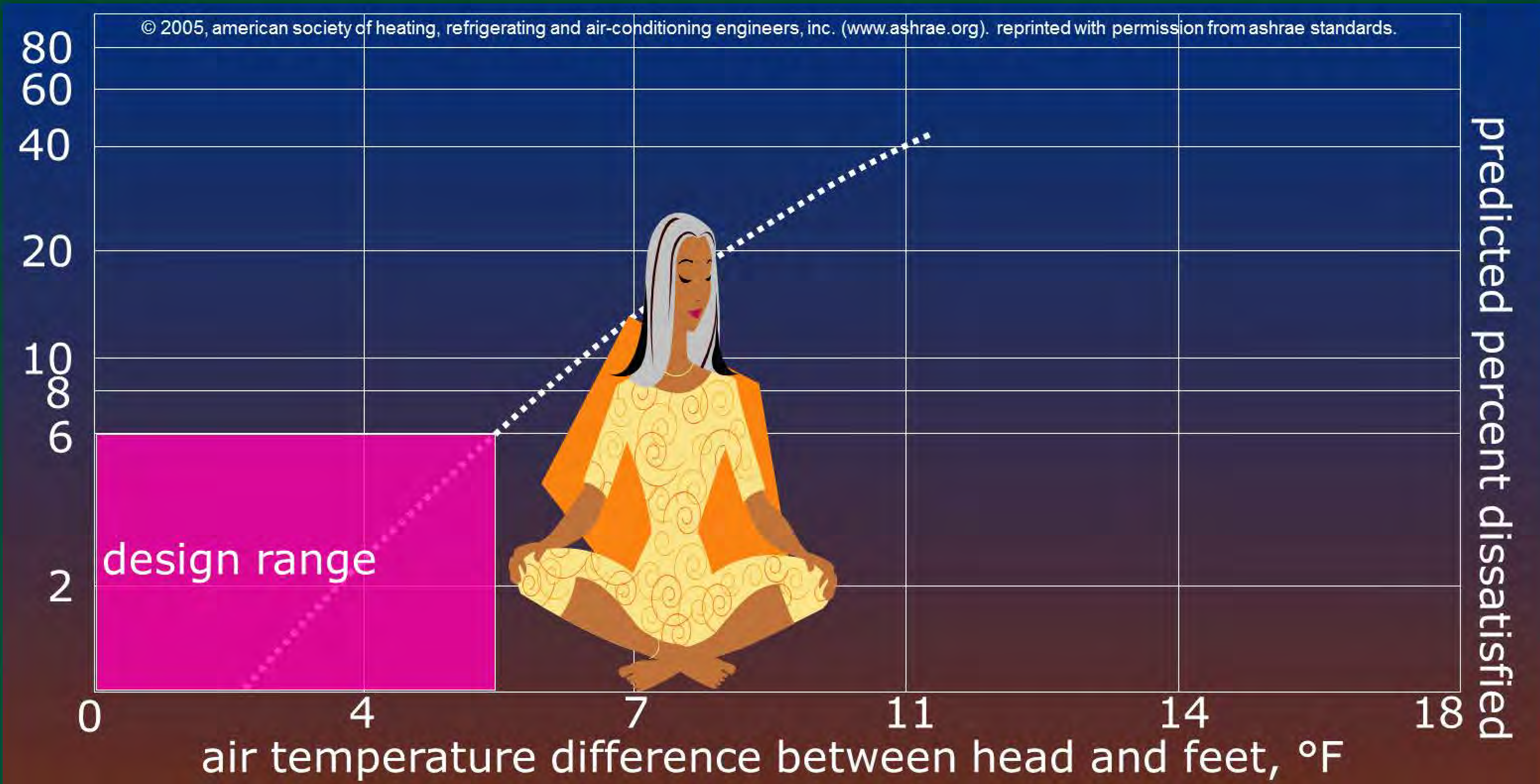
radiant asymmetry



radiant asymmetry

photo credit: gary hayden, p.e., © 2011

temperature stratification



temperature stratification & drafts

Adapted/Credit: Bean, R., Radiant Based HVAC, ASHRAE D.L. Program, 2010

thermal comfort instrumentation

radiant temperature asymmetry

air velocity

operative temperature

air temperature

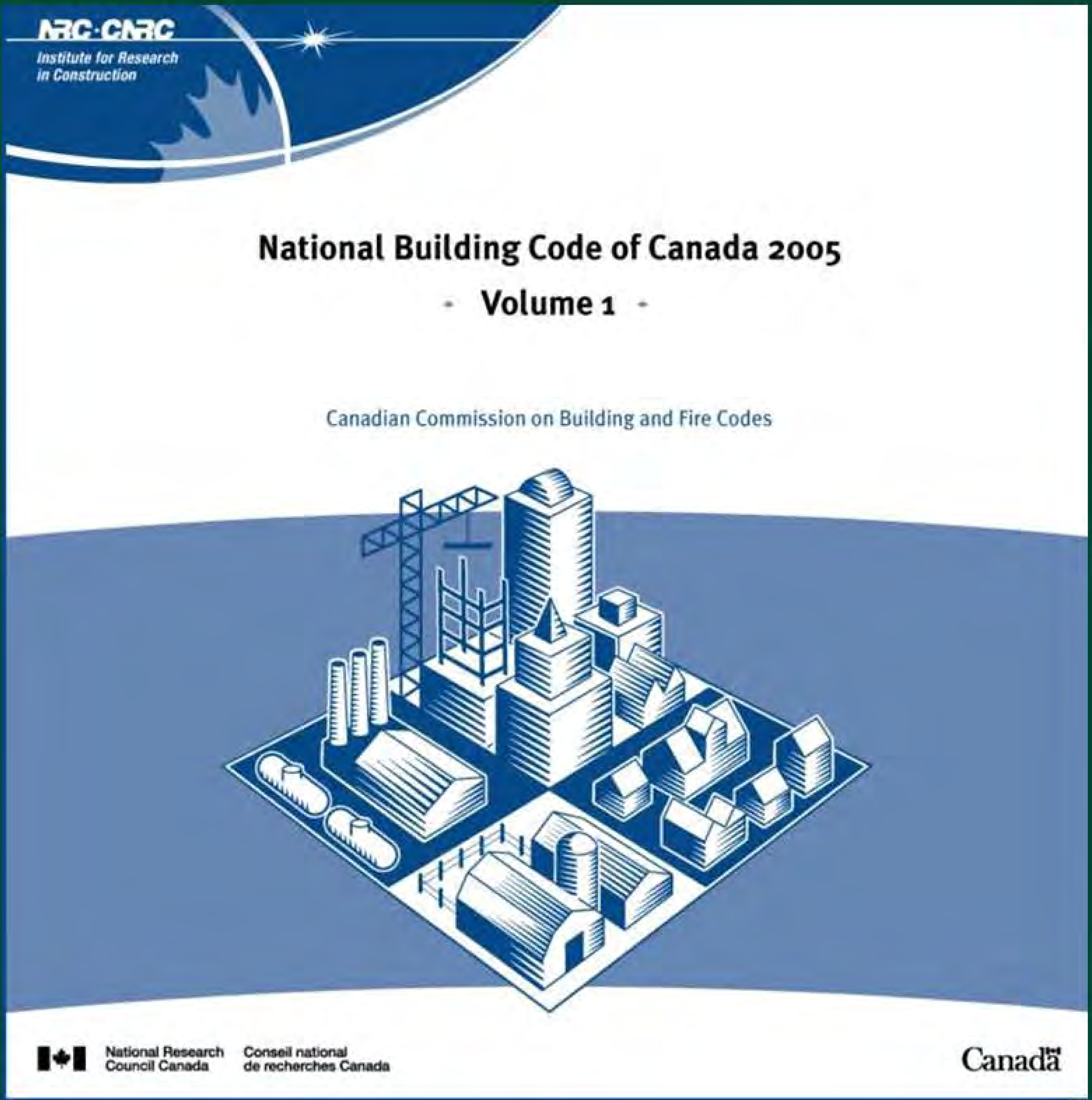
humidity

surface temperature

wbgt

dry heat loss

codes ≠ comfort



$$t_{air} = 22°C$$

in the 2010 appendix…

national building code of canada: section a-5.3.1.2.(1) use of thermal insulation or mechanical systems for environmental control;

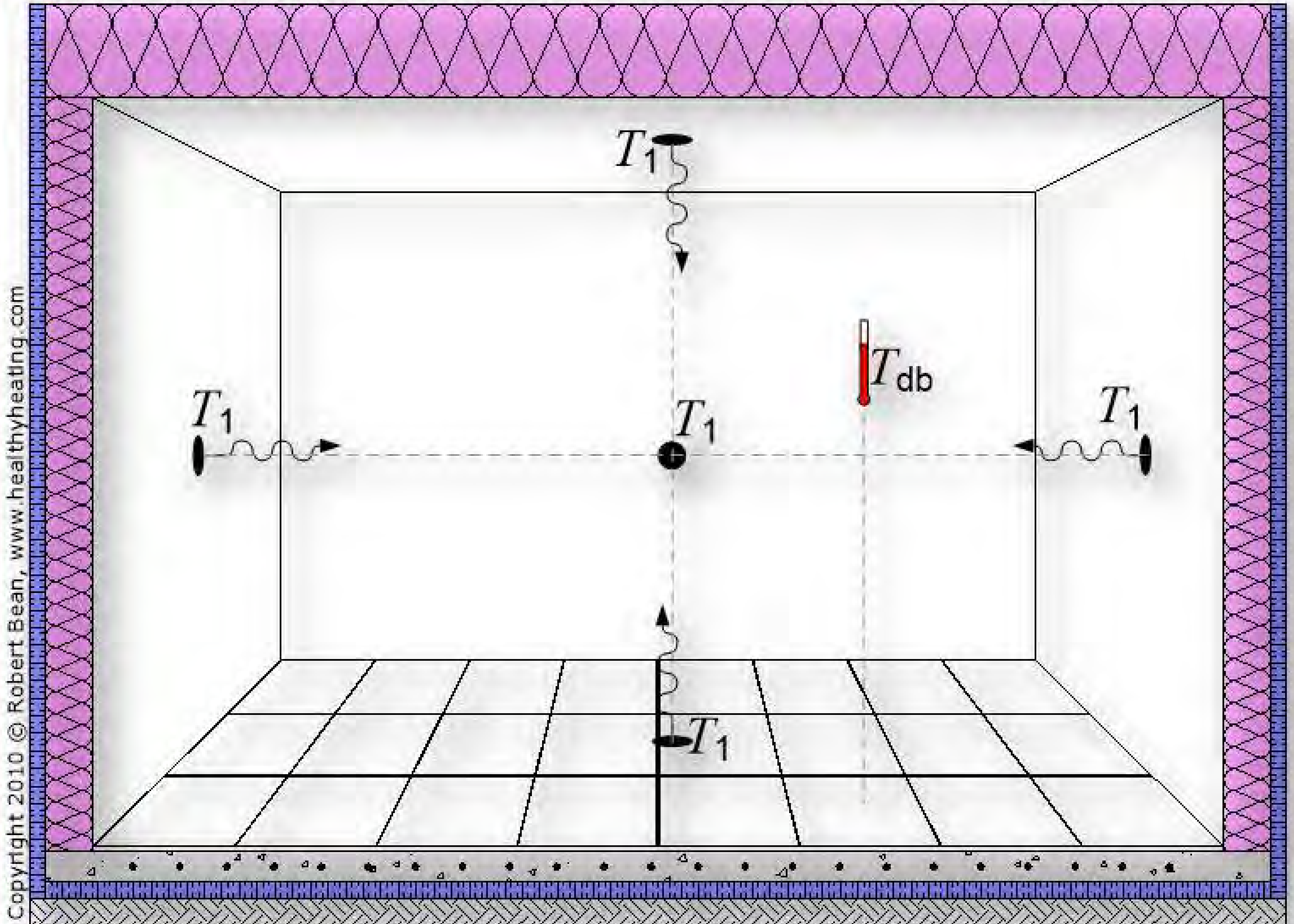
“in addition to controlling condensation, interior surface temperatures must be warm enough to avoid occupant discomfort due to excessive heat loss by radiation.”

from 1857 to the 2010 appendix - good grief

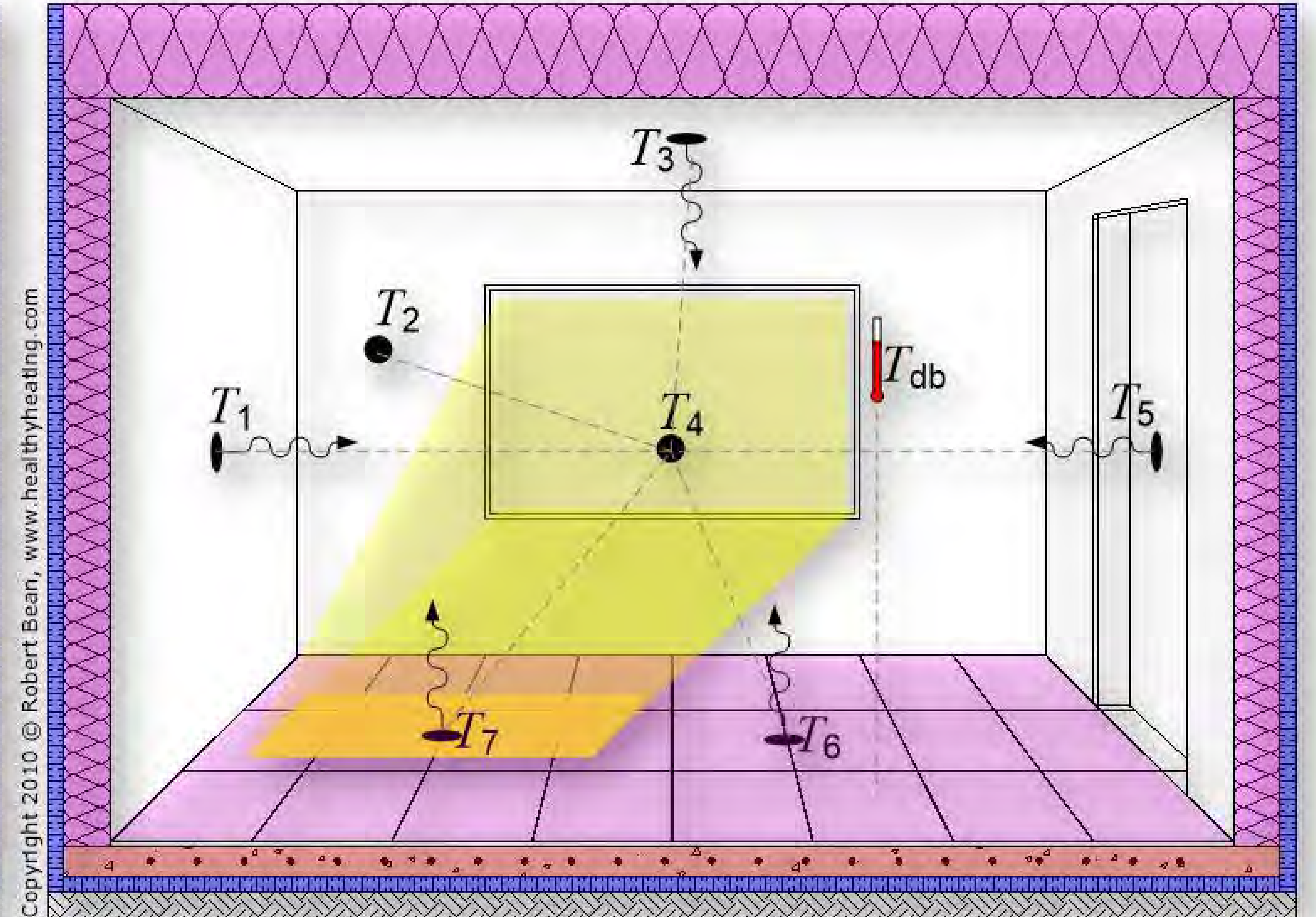
in 1857, "the commissioners of the general board of health advocated as one of the requirements for comfort that the walls of a room be at least as high in temperature as the general temperature of the room, while they included cold walls or floors amongst the conditions which make for discomfort."

source: subjective impressions of freshness in relation to environmental conditions by t. bedford, d.sc., ph.d. and c. g. warner, ph.d., b.sc., of the industrial health research board and the london school of hygiene and tropical medicine, 1939

operative temperature - homogenous or ambiguous?



$$T_o = (h_r\overline{T_r} + h_c T_{db}) / (h_r + h_c)$$



$$T_o = (h_r\overline{T_r} + h_c T_{db}) / (h_r + h_c)$$

mean radiant temperature

Mean radiant temperature calculation methods:

1. area weighted average temperature of the unconditioned surrounding surfaces temperature (AUST, assuming 100% air based hvac) as a simplified proxy for, $\overline{t_r}$ (MRT);
2. the plane radiant temperature, t_{pr}, in six directions;
3. the angle (view) factor between a person and the surrounding surfaces, a function of the shape, the size and the relative positions of the surface in relation to the person;

mean radiant temperature – approach 1

AUST as simplified proxy for MRT

$$\overline{t_r} = t_1 A_1 + t_2 A_2 + \ldots + t_N A_N \,/\, (A_1 + A_2 + \ldots + A_N)$$

where,

$\overline{t_r}$ = mean radiant temperature, °R (K)

t_N = surface temperature of surface *N*, °R (K)

A_N = area of surface ft^2 (m^2)

advantages: simple (relatively)

disadvantages: ignores the human (MRT by definition is in reference to the occupant)

mean radiant temperature – approach 1

Inside temp. exposed surface, t_u (simplified)

$$t_u = t_a - U/h\ (t_a - t_o)$$

where,

t_a = dry-bulb indoor space design, °F (C)

t_o = dry-bulb outdoor space design, °F (C)

U = overall heat transfer coefficient, Btu/h□ft^2□F

h = natural-convection coefficient of the inside surface, Btu/h□ft^2□F (W/m^2□ K)

mean radiant temperature – approach 1

Inside temp. exposed surface, t_u (simplified)

$$t_u = t_a - U/h\ (t_a - t_o)$$

Natural convection: heat transfer coefficients, *h*		
surface (orientation)	W/(m²·K)	Btu/h·ft²·°F
horizontal surface with heat flow up	9.26	1.63
vertical surface (wall)	9.09	1.46
horizontal surface with heat flow down	8.29	1.08
Source: ASHRAE Handbook – HVAC Systems and Equipment, Chapter 6, 2012, section 6.5 Formula 13		

mean radiant temperature – approach 1

calculating inside surface temperatures for determining mean radiant

	A	B	C	D	E
1					
2		Determining the inside surface temperature (t_u) of outdoor exposed walls and outdoor exposed floors or ceilings: simplfied method (ignores short and long wave energy and other heat sources).			
3		ref.: Equation 13, 2012 ASHRAE Handbook—HVAC Systems and Equipment, Section 6.5			
4		dry-bulb outdoor design air temperature, °F	t_o	32	enter
5		dry-bulb indoor space design air temperature, °F	t_a	72	enter
6		overall heat transfer coefficient of wall, ceiling, or floor, Btu/h·ft2·°F (use weighted average)	U	0.10	enter
7		natural-convection coefficient of the inside surface of an outdoor exposed wall or ceiling	h	1.08	select
8		h = 1.63 Btu/h·ft2·°F for a horizontal surface with heat flow up			
9		h = 1.46 Btu/h·ft2·°F for a vertical surface (wall)			
10		h = 1.08 Btu/h·ft2·°F for a horizontal surface with heat flow down			
11					
12		inside surface temperature of outdoor exposed surface, °F	t_u	68.30	results
16		Use of this spreadsheet is governed by the legal disclaimer at http://www.healthyheating.com/legal.htm			
17					

mean radiant temperature – approach 1

Table 2 Indoor Surface Heat Transfer Coefficient h_i in Btu/h·ft²·°F, Vertical Orientation (Still Air Conditions)

			Winter Conditions[b]			Summer Conditions[c]		
Glazing ID[a]	Glazing Type	Glazing Height, ft	Glass Temp., °F	Temp. Diff., °F	h_i, Btu/h·ft²·°F	Glass Temp., °F	Temp. Diff., °F	h_i, Btu/h·ft²·°F
1	Single glazing	2	17	53	1.41	89	14	1.41
		4	17	53	1.31	89	14	1.33
		6	17	53	1.25	89	14	1.29
5	Double glazing with	2	45	25	1.36	89	14	1.41
	1/2 in. air space	4	45	25	1.27	89	14	1.33
		6	45	25	1.22	89	14	1.29
23	Double glazing with	2	56	14	1.31	87	12	1.38
	e = 0.1 on surface 2	4	56	14	1.23	87	12	1.31
	and 1/2 in. argon space	6	56	14	1.19	87	12	1.27
43	Triple glazing with	2	63	7	1.25	93	18	1.45
	e = 0.1 on surfaces 2 and 5	4	63	7	1.18	93	18	1.36
	and 1/2 in. argon spaces	6	63	7	1.15	93	18	1.32

Notes:
[a]Glazing ID refers to fenestration assemblies in Table 4.
[b]Winter conditions: room air temperature t_i = 70°F, outdoor air temperature t_o = 0°F, no solar radiation
[c]Summer conditions: room air temperature t_i = 75°F, outdoor air temperature t_o = 89°F, direct solar irradiance E_D = 248 Btu/h·ft²
$h_i = h_{ic} + h_{iR} = 1.46(\Delta T/L)^{0.25} + \varepsilon\sigma(T_i^4 - T_g^4)/\Delta T$, where $\Delta T = T_i - T_g$, °R; L = glazing height, ft; T_g = glass temperature, °R; σ = Stefan-Boltzmann constant; and ε = surface emissivity.

Fenestration, Chapter 15.6, 2009 ASHRAE Handbook—Fundamentals

mean radiant temperature – approach 1

AUST as simplified proxy for MRT

$$\bar{t}_r = t_1 A_1 + t_2 A_2 + \ldots + t_N A_N \,/\, (A_1 + A_2 + \ldots + A_N)$$

surface temp of surface

area of panel

mean radiant temperature – approach 2

MRT from plane radiant temperature - standing

$$\overline{t_r} = \{0.08[t_{pr(up)} + t_{pr(down)}] + 0.23[t_{pr(right)} + t_{pr(left)}] + 0.35[t_{pr(front)} + t_{pr(back)}]\} / [2(0.08+0.23+0.35)]$$

where,

t_{pr} = plane radiant temperature, °R (K)

advantages: simple (relatively)

disadvantages: only describes thermal radiation in one direction

mean radiant temperature – approach 2

MRT from plane radiant temperature - seated

$$\overline{t_r} = \{0.18[t_{pr(up)} + t_{pr(down)}] + 0.22[t_{pr(right)} + t_{pr(left)}]$$
$$+ 0.30[t_{pr(front)} + t_{pr(back)}]\} / [2(0.18+0.22+.30)]$$

where,

t_{pr} = plane radiant temperature, °R (K)

advantages: simple (relatively)

disadvantages: only describes thermal radiation in one direction

mean radiant temperature – approach 3

MRT from angle (view) factor for a simple homogenous space

$$\overline{t_r} = t_1 F_{p\text{-}1} + t_2 F_{p\text{-}2} + \ldots + t_N F_{p\text{-}N}$$

where,

$\overline{t_r}$ = mean radiant temperature, °R (K)

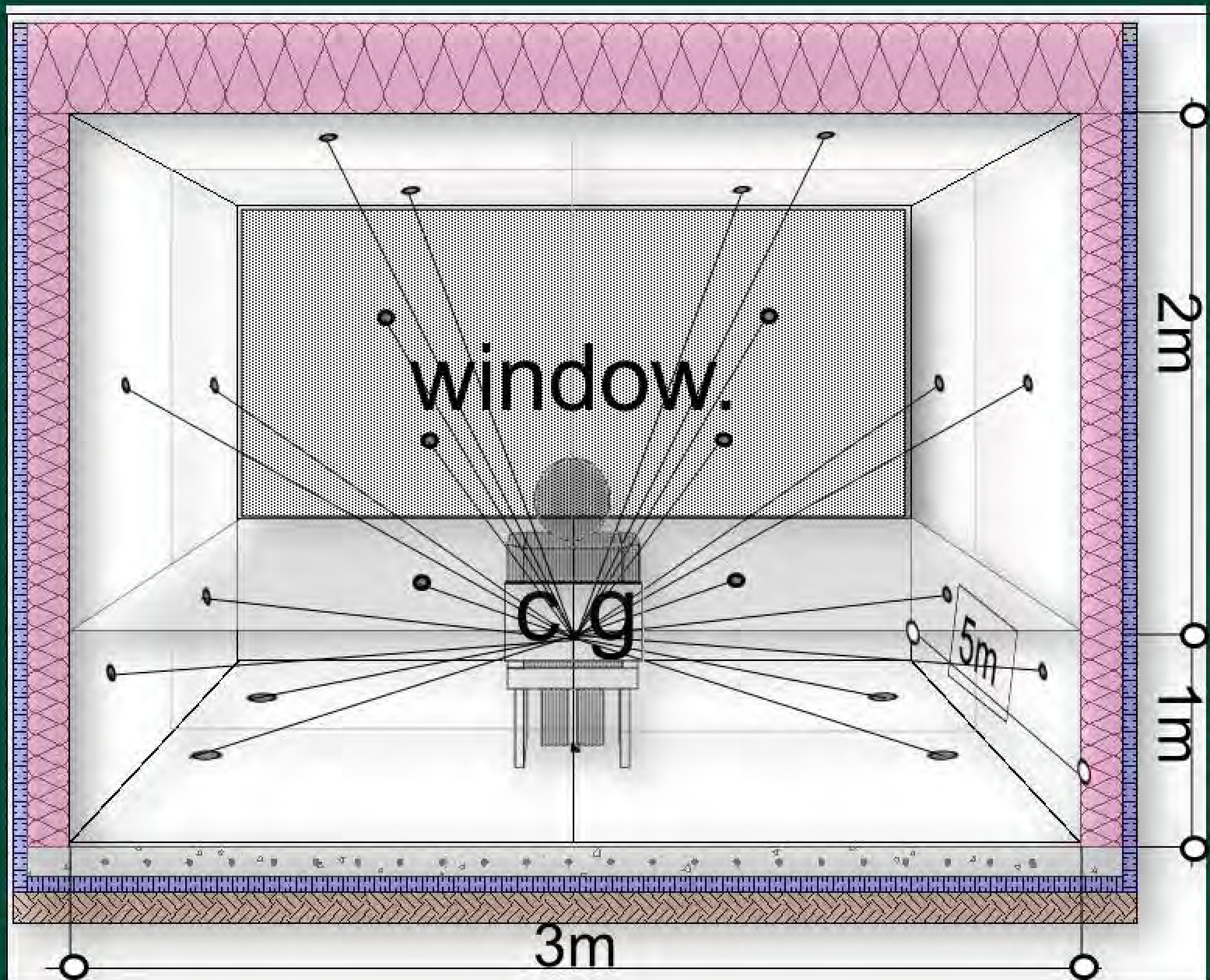
t_N = surface temperature of surface *N*, °R (K)

$F_{p\text{-}N}$ = angle factor between a person & surface *N*

advantages: includes the occupant

disadvantages: a tedious calculation, view factor graphs for rectangular surfaces are estimates only

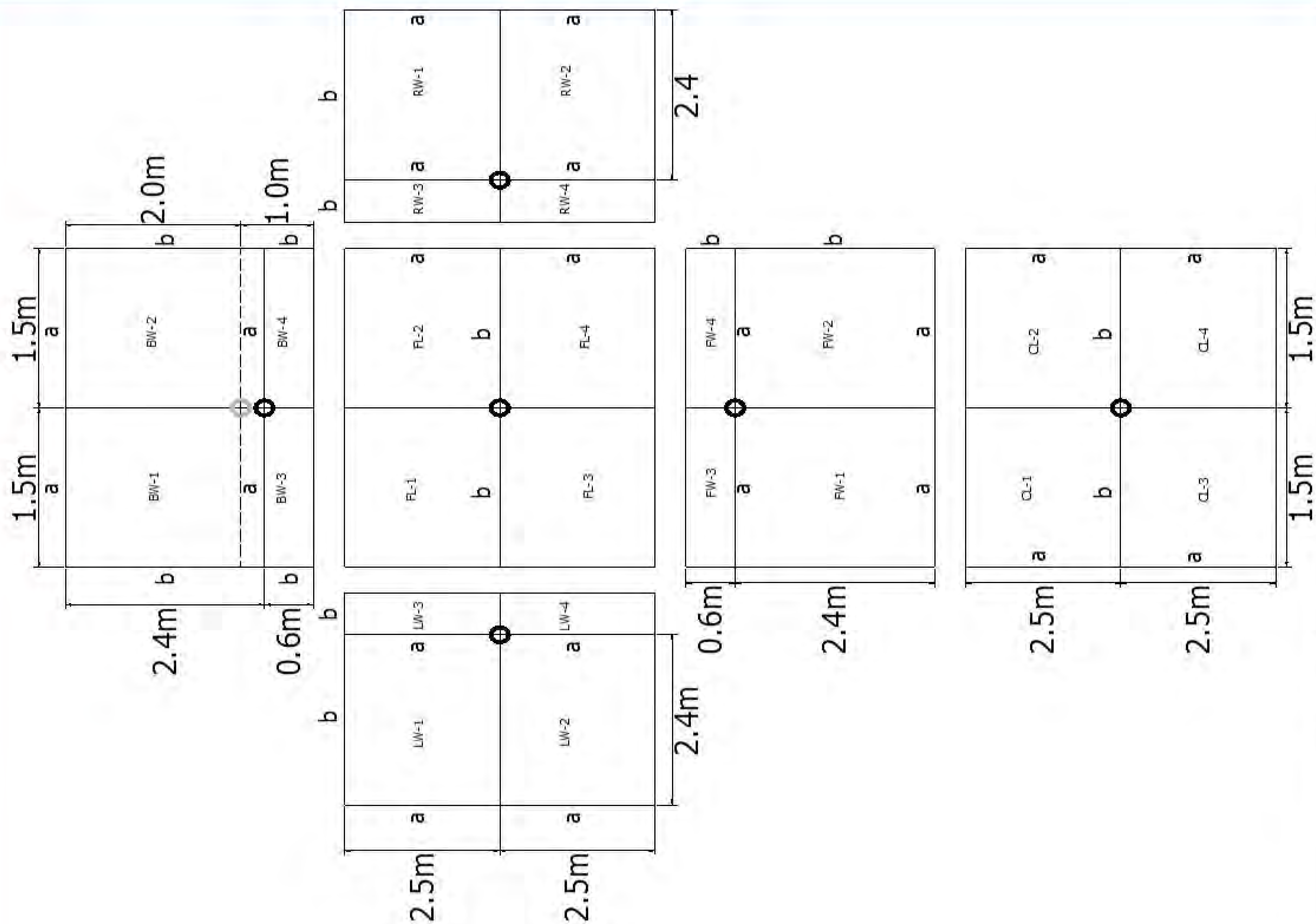
mean radiant temperature – approach 3



angle factors

a minimum MRT evaluation calculates each surface quadrant above and below the center of gravity (c.g.).

mean radiant temperature – approach 3



Angle factor, $F_{p\text{-}N}$ results for seated individuals	
Surface	$F_{p\text{-}N}$
Floor	0.32
Ceiling	0.12
Front wall	0.03
Window	0.06
Back wall	0.09
Right side wall	0.19
Left side wall	0.19
Unity	1

Reference: Table 2.2, REHVA Guidebook No. 7, pg. 12

mean radiant temperature – approach 3

- Simplified method for calculating angle factors

$$F_{p\text{-}N} = F_{\max}\,(1 - e^{-(a/c)/\tau})\,(1 - e^{-(b/c)/\gamma})$$

where,

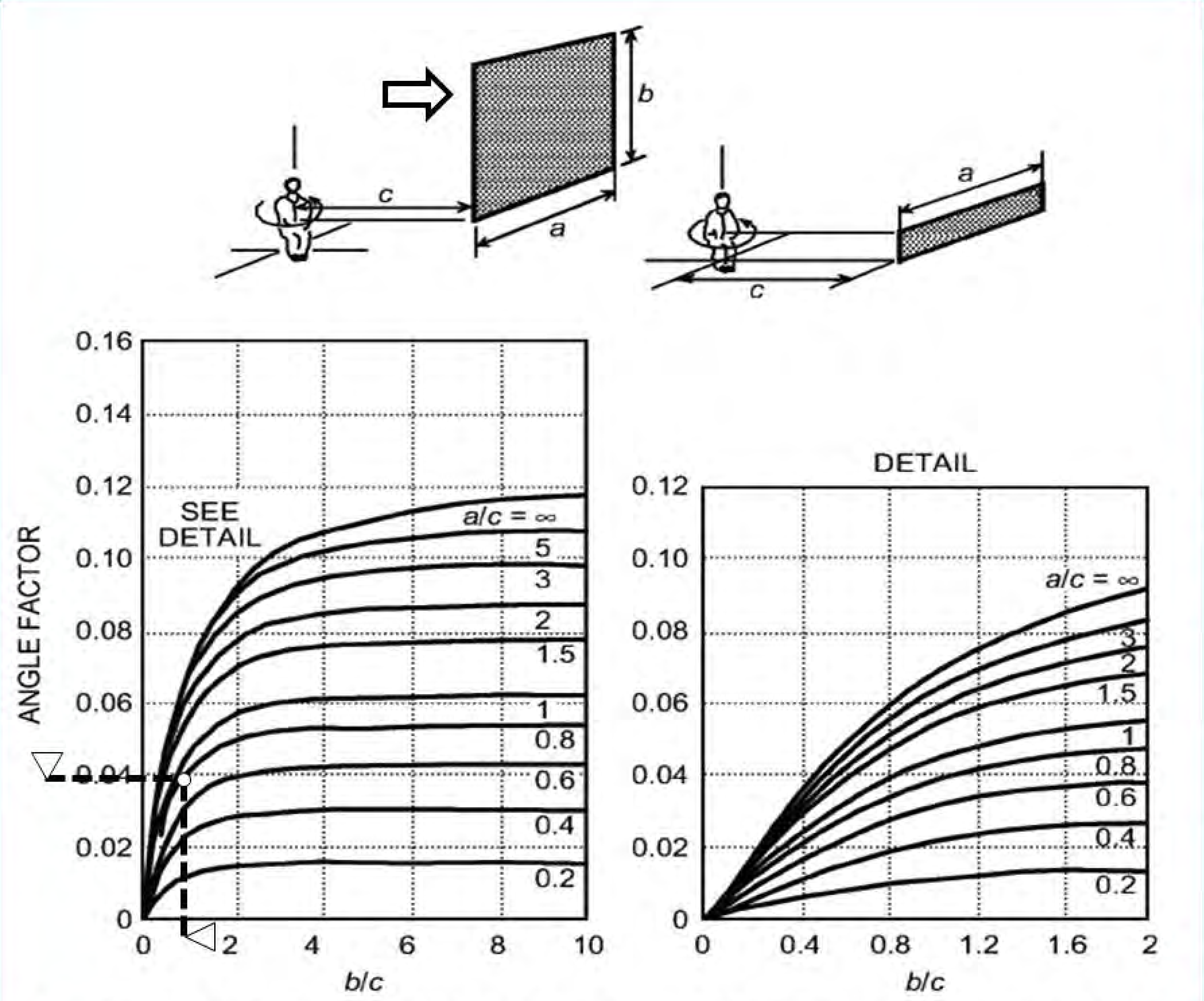
$$\tau = A + B\,(a/c)$$

$$\gamma = C + D\,(b/c) + E\,(a/c)$$

Terms for calculating angle factors (Ref.: Table 2.1, REHVA Guidebook No. 7, pg. 11, 2007)

Occupant position	F_{max}	A	B	C	D	E
Seated person, Figure B Vertical surfaces: wall, window	0.118	1.216	0.169	0.717	0.087	0.052
Seated person, Figure A Horizontal surfaces: floor, ceiling	0.116	1.396	0.130	0.951	0.080	0.055

mean radiant temperature – approach 3



B. VERTICAL RECTANGLE (ABOVE OR BELOW CENTER OF PERSON)

solve for b/c & a/c

example: $F_{p\text{-}1}$

a = 4m

b = 3m

c = 5m

b/c = 3/5 = 0.6

a/c = 4/5 = 0.8

$F_{p\text{-}1}$ = 0.039

Image source/credit: Fig. 3 Mean Value of Angle Factor Between Seated Person and Horizontal or Vertical Rectangle when Person is Rotated Around Vertical Axis (Fanger 1982), chapter 9.11 2009 ASHRAE Handbook—Fundamentals

mean radiant temperature – approach 3

MRT from angle (view) factor

$$\bar{t}_r = t_1 F_{p\text{-}1} + t_2 F_{p\text{-}2} + \ldots + t_N F_{p\text{-}N}$$

surface temp of panel

angle factor

mean radiant temperature – approach 3

- Operative temperature (t_o)

$$t_o = (h_r \overline{t_r} + h_c t_{db}) / (h_r + h_c)$$

where,

h_c = convective heat transfer coefficient

h_r = linear radiative heat transfer coefficient

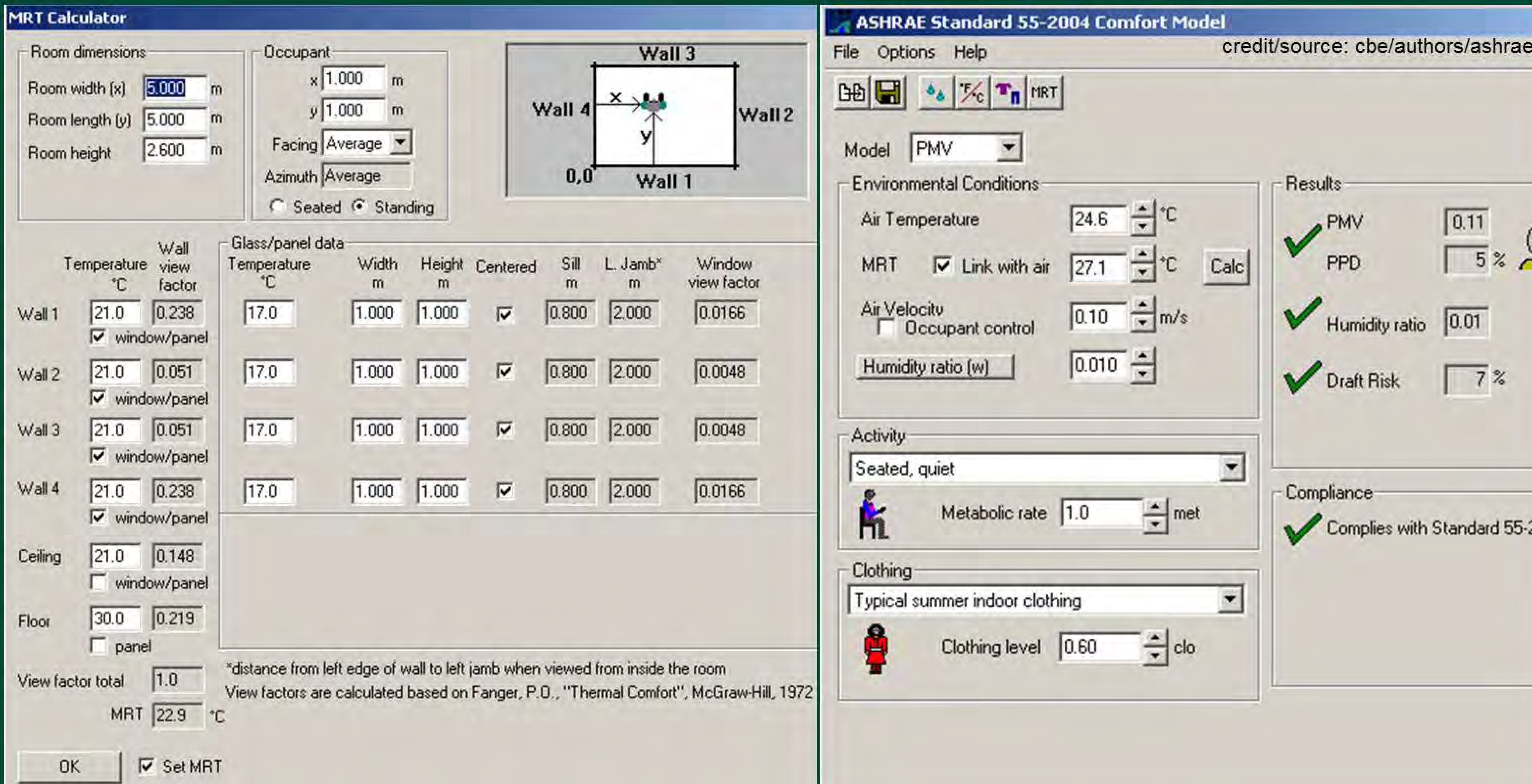
t_{db}= air (dry bulb) temperature

$\overline{t_r}$ = mean radiant temperature

simple form,

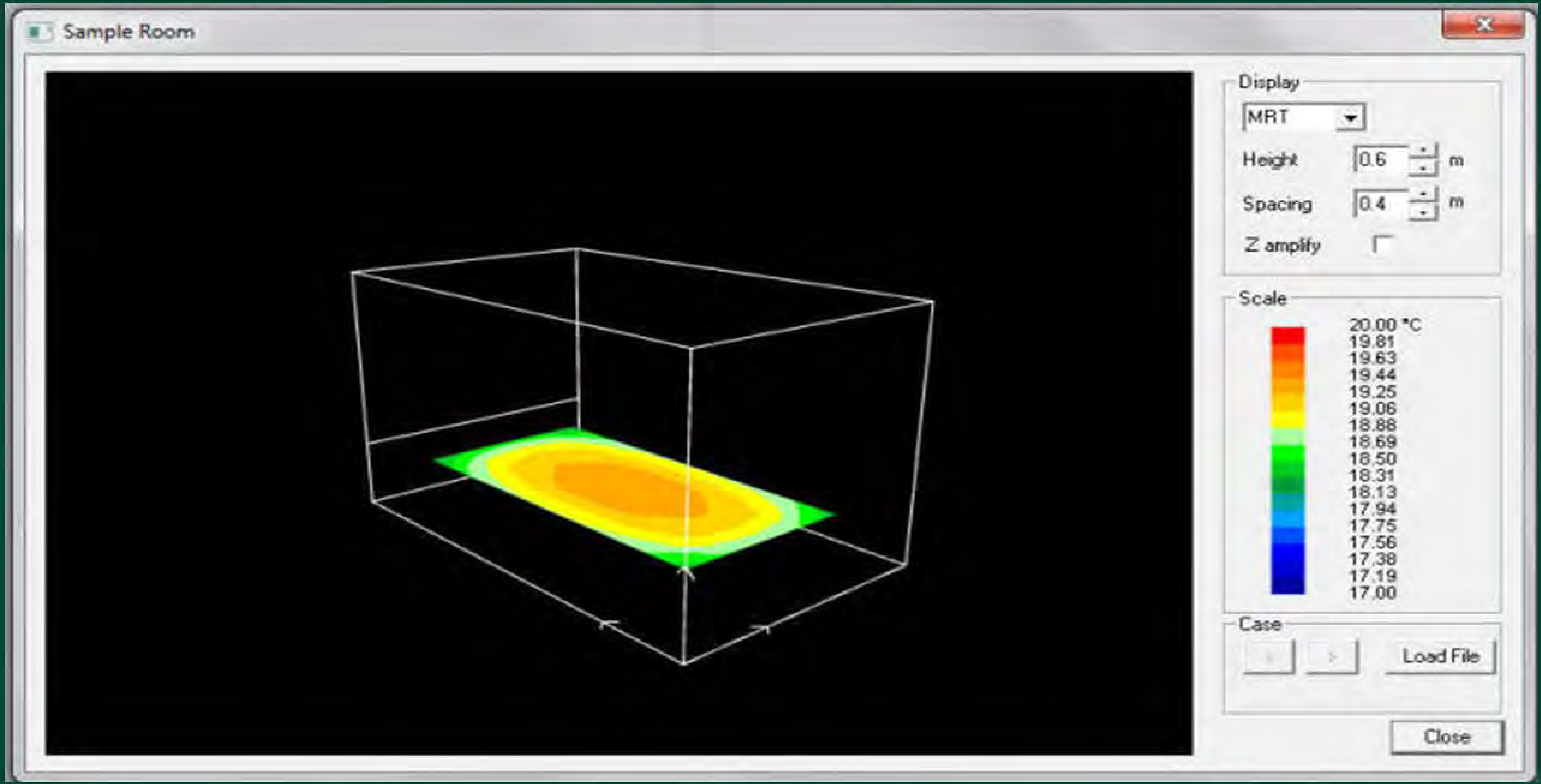
$$t_o = (\overline{t_r} + t_{db}) / 2$$

…or use the software

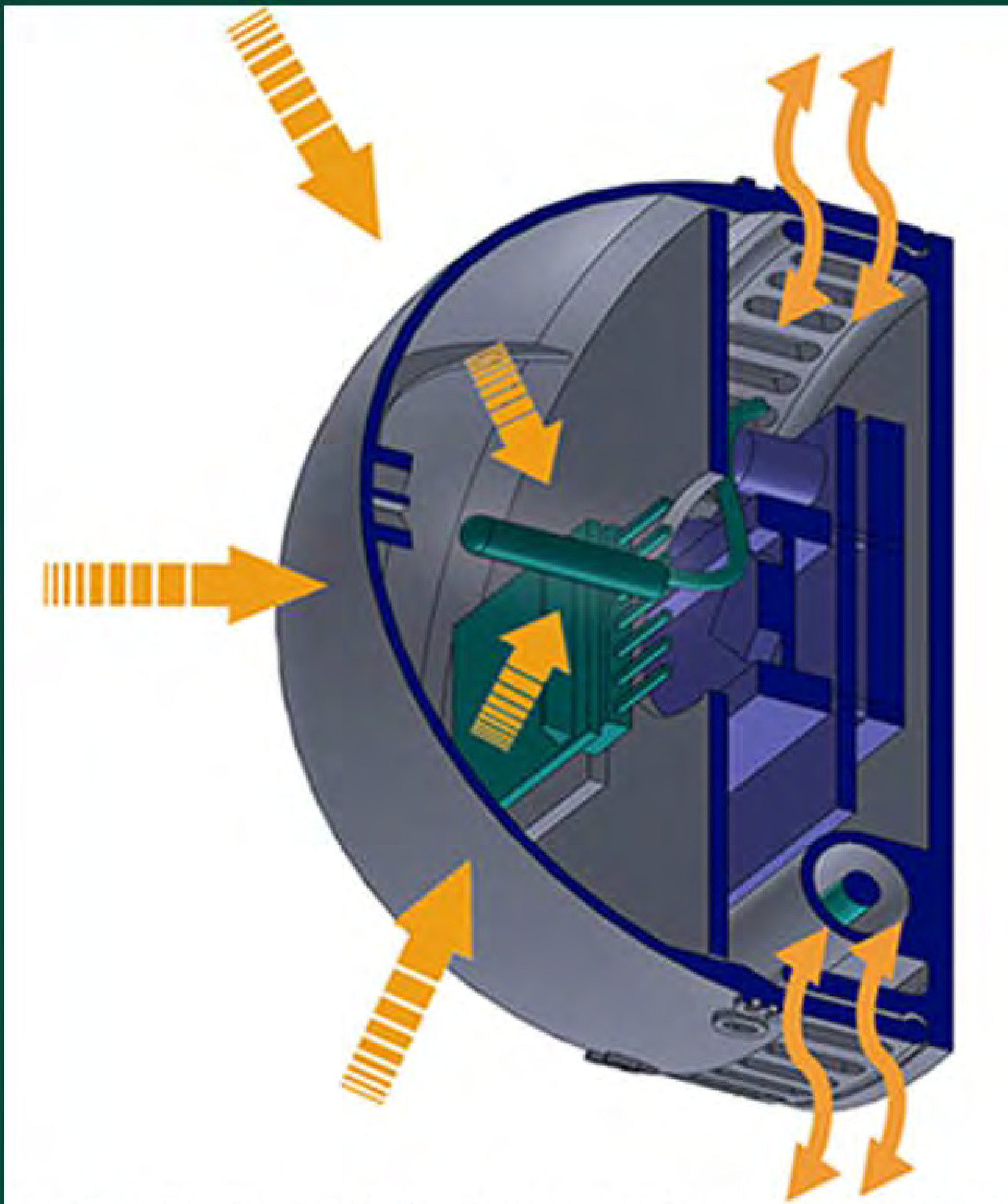


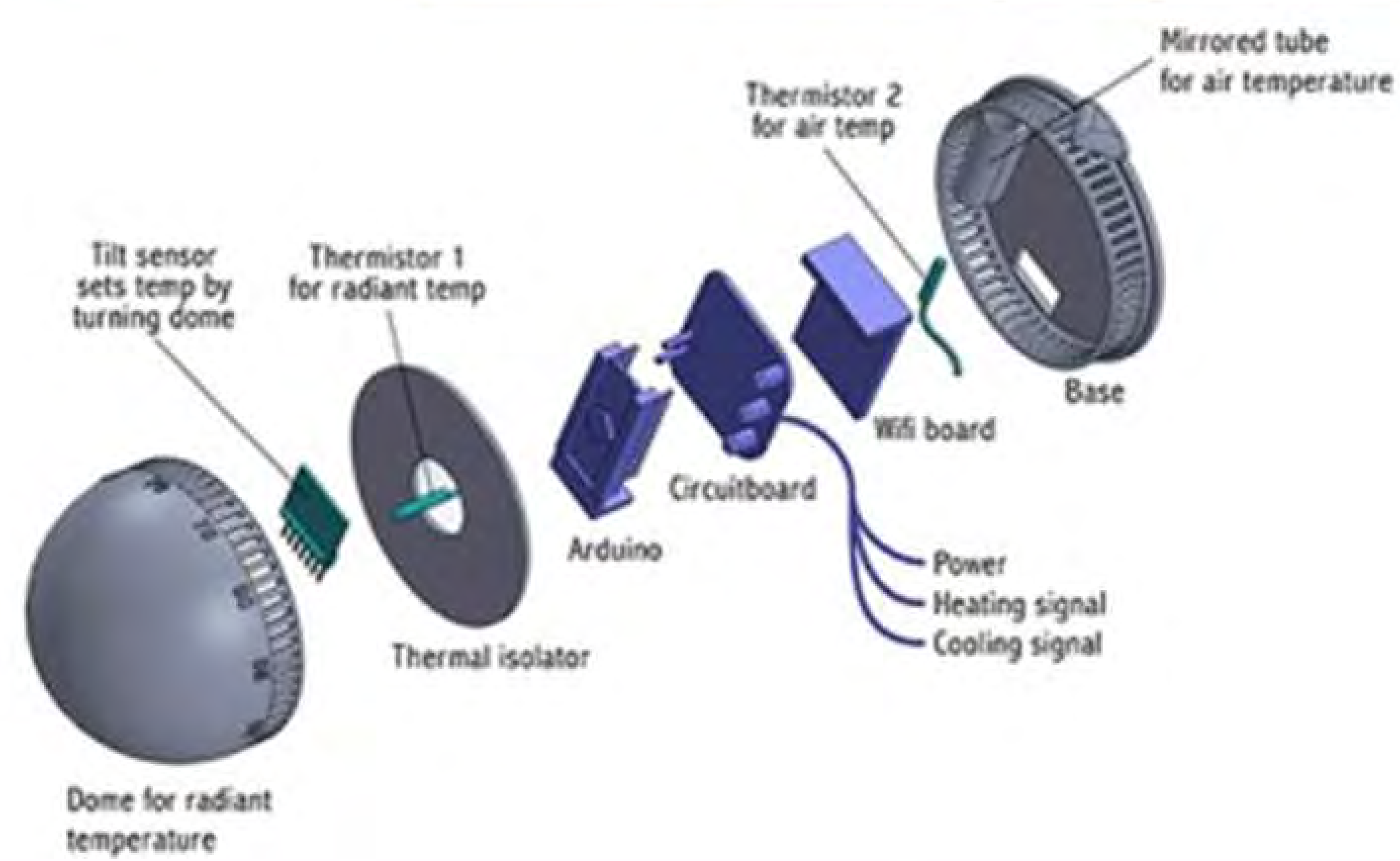
your ASHRAE dollars at work

3D output screen shot: ASHRAE RP-1383 illustrating the MRT color contours at the seated level (0.6m). The 3D tool can also illustrate PMV/PPD as per ANSI/ASHRAE Standard 55 - Thermal Environmental Conditions for Human occupancy.



operative thermostats





http://faludidesign.com/design/Thermostat/_Thermostat_index.html

operative thermostats

thermal ambassadors

need to speak the

language of the

occupants

human factor thermostats

mean radiant temperature (mrt) plus dry bulb
= operative temperature = what we feel.

operative thermostats

wireless stat / fully modulating

senses operative temperature

1 page installation manual most of it pictures

no batteries

1st produced in 1943

peter pan homes built in never-neverland

for those who

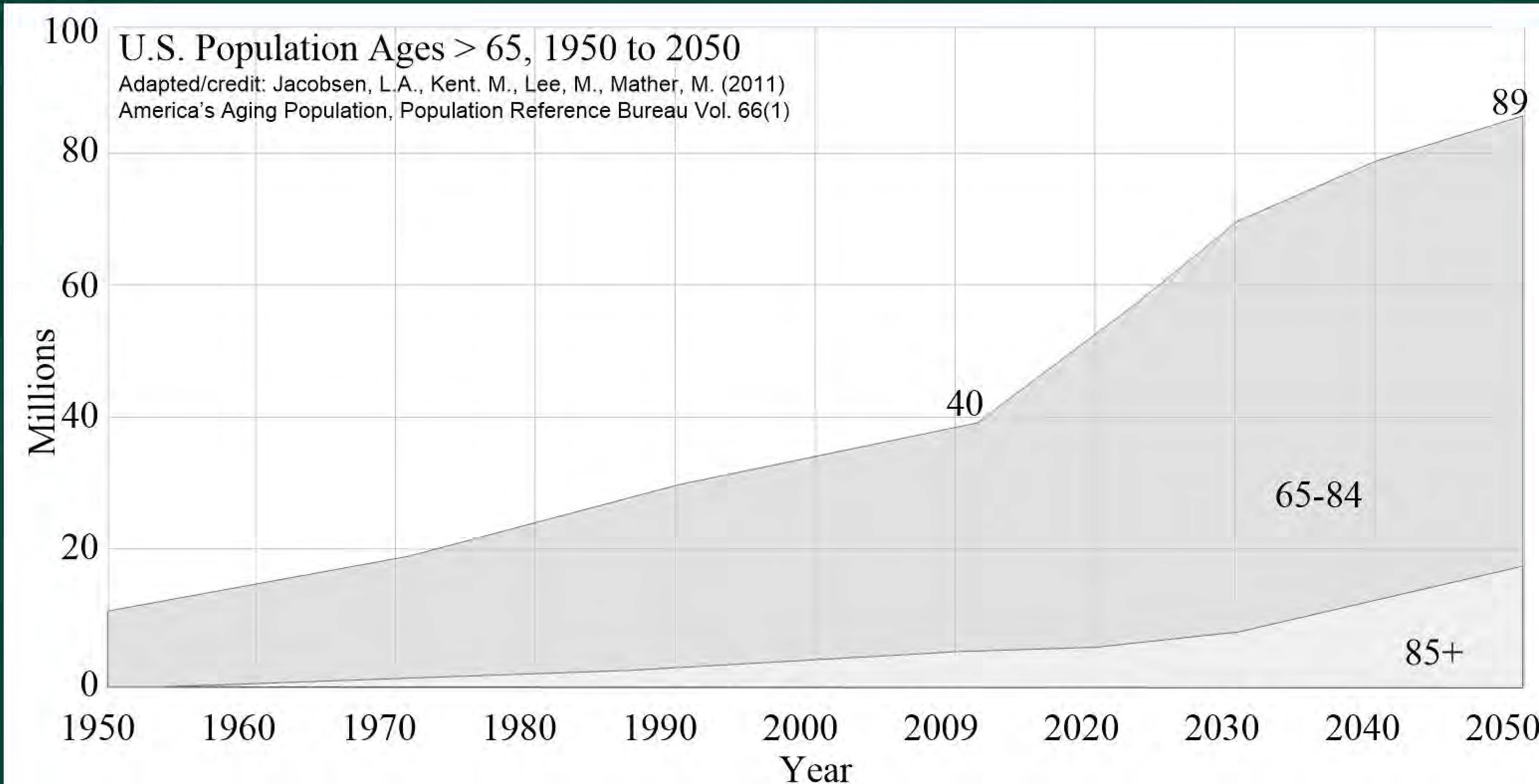
never grow old,

never become injured

and never get sick

Image source/credit: http://upload.wikimedia.org/wikipedia/commons/1/15/Peter_Pan_1915_cover.jpg

people do get old



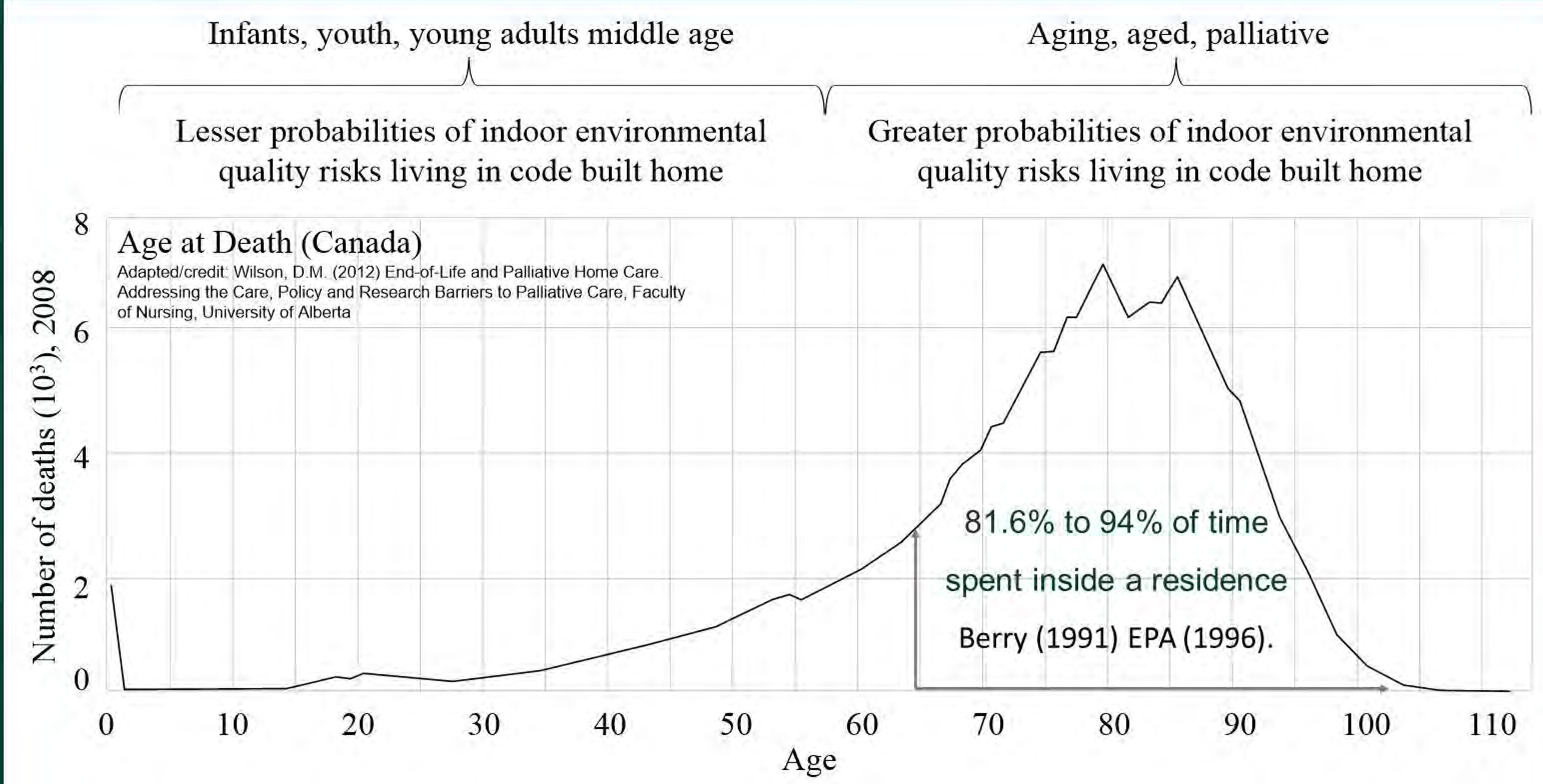
people do get old @ home

TABLE 2-1 Percentage of Time Spent Indoors as a Function of Age		
Population, age in years	Fraction of Time Spent in Residence, %	Fraction of Total Time Spent Indoors
General population[a]	69	86.5-9 1.6
Children and youth[b]		
Birth to <l	75.7	94
1 - <2	72.7	94
2 - <3	67.3	91.4
3 - <6	66	88.8
6 - <11	60.6	83.4
11 - <16	60.8	87.5
16 - <21	56.9	86.6
Elderly {>64)[c]	**81.6-95**	

[a] Bernstein (2008) Dales (2008) Klepeis (2001).
[b] EPA (2009).
[c] Berry (1991) EPA (1996).

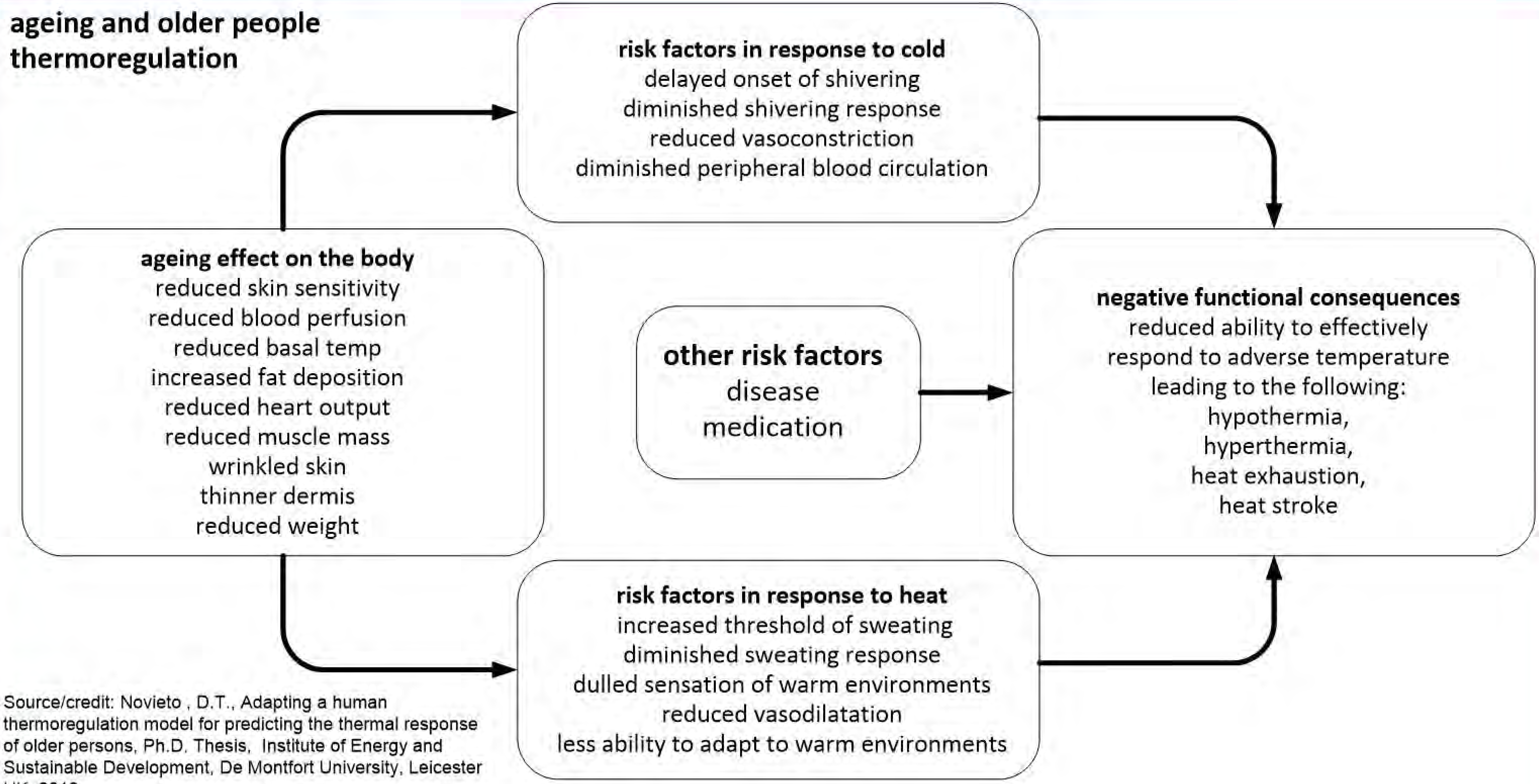
Source: Climate Change: The Indoor Environment and Health (2011) Committee on the Effect of Climate Change on Indoor Air Quality and Public Health, Board on Population Health and Public Health Practice, Institute of Medicine of The National Academies, Washington, D.C.

people do get old & sick @ home & die



falling though the cracks

ageing and older people thermoregulation



Source/credit: Novieto , D.T., Adapting a human thermoregulation model for predicting the thermal response of older persons, Ph.D. Thesis, Institute of Energy and Sustainable Development, De Montfort University, Leicester UK, 2013

infirm, injured, aged, & palliative care persons

manual dexterity

visual acuity

cognitive abilities

endocrine, nervous,

respiratory, muscular,

cardiovascular systems

adaptive and natural - for whom?

how easy is *adaptive comfort* and *natural ventilation* for someone with advanced arthritis, cerebral palsy, multiple sclerosis, myalgic encephalomyelitis or Parkinson's etc…

technological solutions – for whom?

how easy is

programing thermostats

and

HVAC maintenance

for someone with

macular degeneration,

cataracts, vascular dementia

or early onset Alzheimer's?

if you don't fit into the 'norm'

TECHNICAL SPECIFICATION

ISO/TS 14415

First edition 2005-04-15

Ergonomics of the thermal environment — Application of International Standards to people with special requirements

Ergonomie de l'environnement thermique — Application des Normes internationales aux personnes ayant des exigences particulières

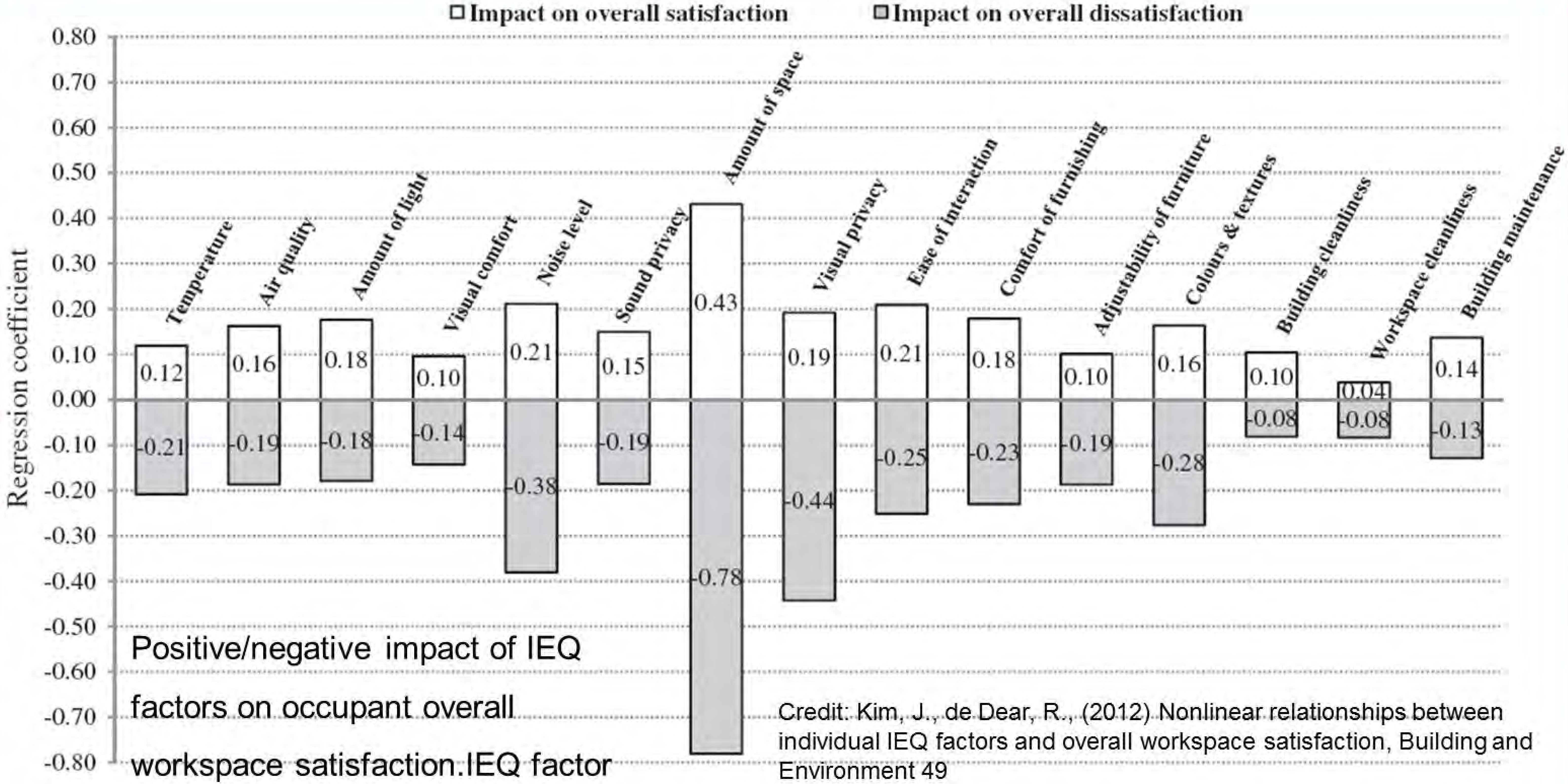
Reference number ISO/TS 14415:2005(E)

© ISO 2005

ISO/TS 14415:2005(E) Ergonomics of the thermal environment — Application of International Standards to people with special requirements

- Sensory impairment and paralysis
- Difference in body shape
- Impairment of sweat secretion
- Impairment of vasomotor control
- Differences in metabolic rate
- Influence of thermal stress on other physiological functions

post occupancy surveys



Positive/negative impact of IEQ factors on occupant overall workspace satisfaction.IEQ factor

Credit: Kim, J., de Dear, R., (2012) Nonlinear relationships between individual IEQ factors and overall workspace satisfaction, Building and Environment 49

our favorite clients

client, "…the guiding principles that describe our design are (1) build to last, (2) simple to maintain, and (3) healthy/comfortable to live in. I know some people might cringe at what I'm about to say. For us, energy is not as important as a healthy/comfortable house…"

our favorite clients

"I adjusted the system temperature, 2°F (1°C) at a time, and now down to 96°F (36°C). At 97°F (36°C) I got a delta t of 23°F (13°C). With the lead boiler running 19 hours a day, outside temperature was -7°F(-22°C), Ambient room temperature is between 62°F (17°C)…we'll see what it does with the system at 96°F (36°C). "

55,000ft^2 (5110m^2) multipurpose industrial facility

…& favorite stories (and story's)




HVAC for a lifetime: dedicated ventilation

if satisfying a thermostat setting

destroys the process of

decontamination, deodorization and

dehumidification of ventilation air

the HVAC system is dysfunctional.

imho

HVAC for a lifetime: dedicated thermal comfort

elderly, injured, infirm and palliative care

final thought…

buildings are not

uncomfortable

people are

HVAC in the real world: part 2

e^5

energy, eXergy, efficiency,

entropy, efficacy

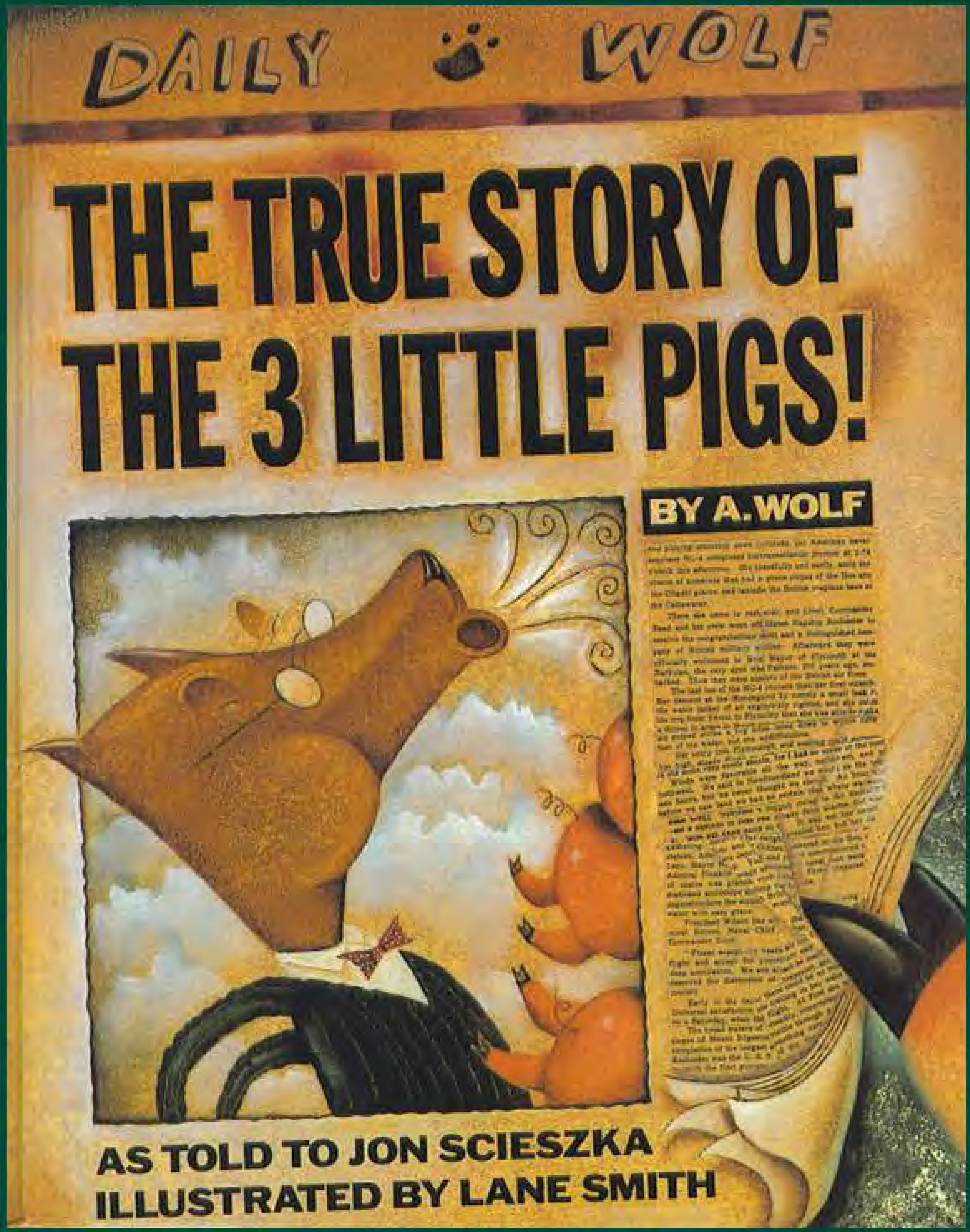
Robert Bean, R.E.T., P.L. (Eng.)
President, Indoor Climate Consultants Inc
Technical Director, www.healthyheating.com
info@healthyheating.com

the three little pigs must die!

combustion

customization

complexity



the graph

interactions and connections

building performance, HVAC exchanger surface areas

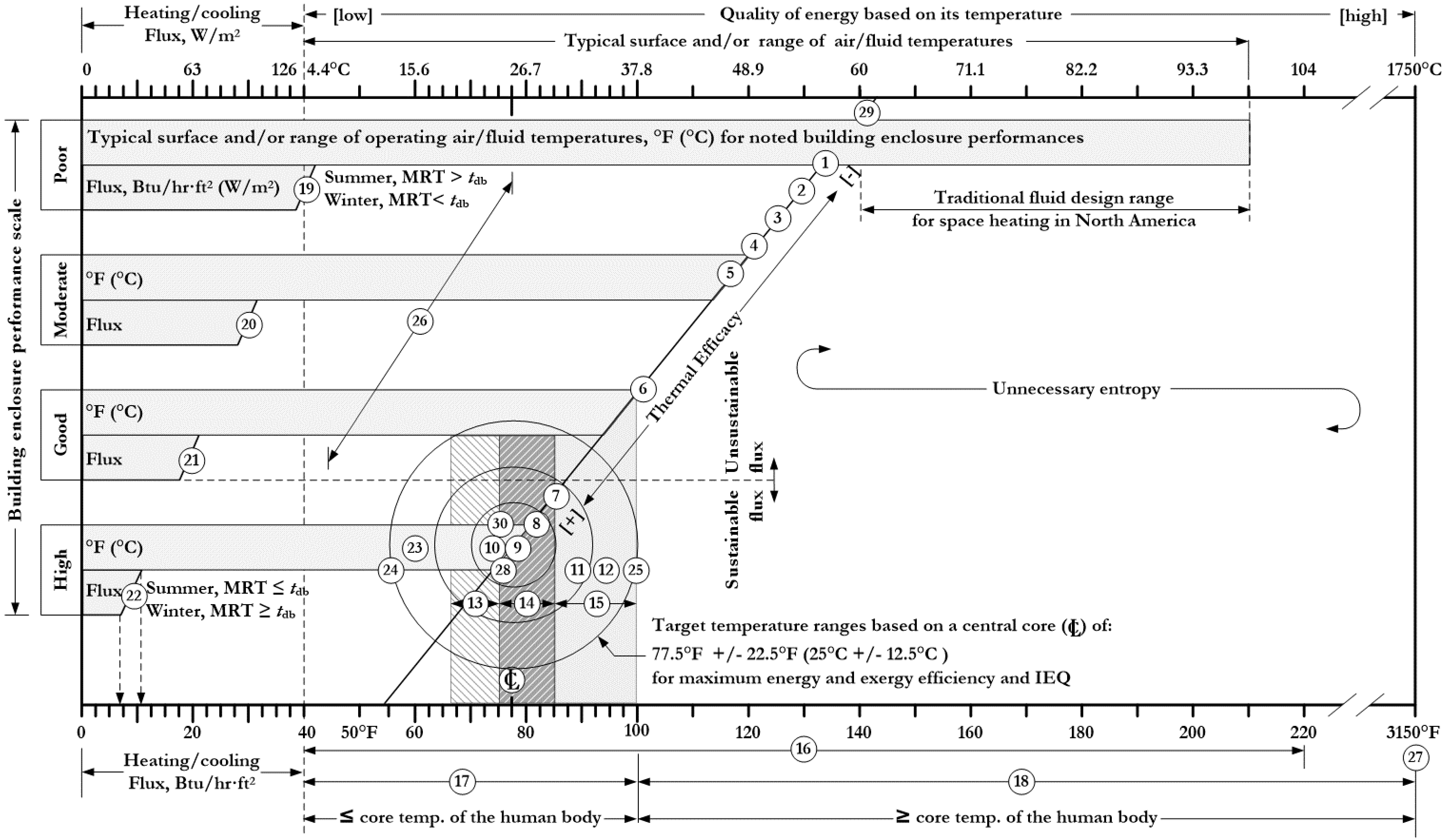
& temperatures.

relationship between, energy, exergy, efficiency, entropy & efficacy.

low temperature heating and high temperature cooling.

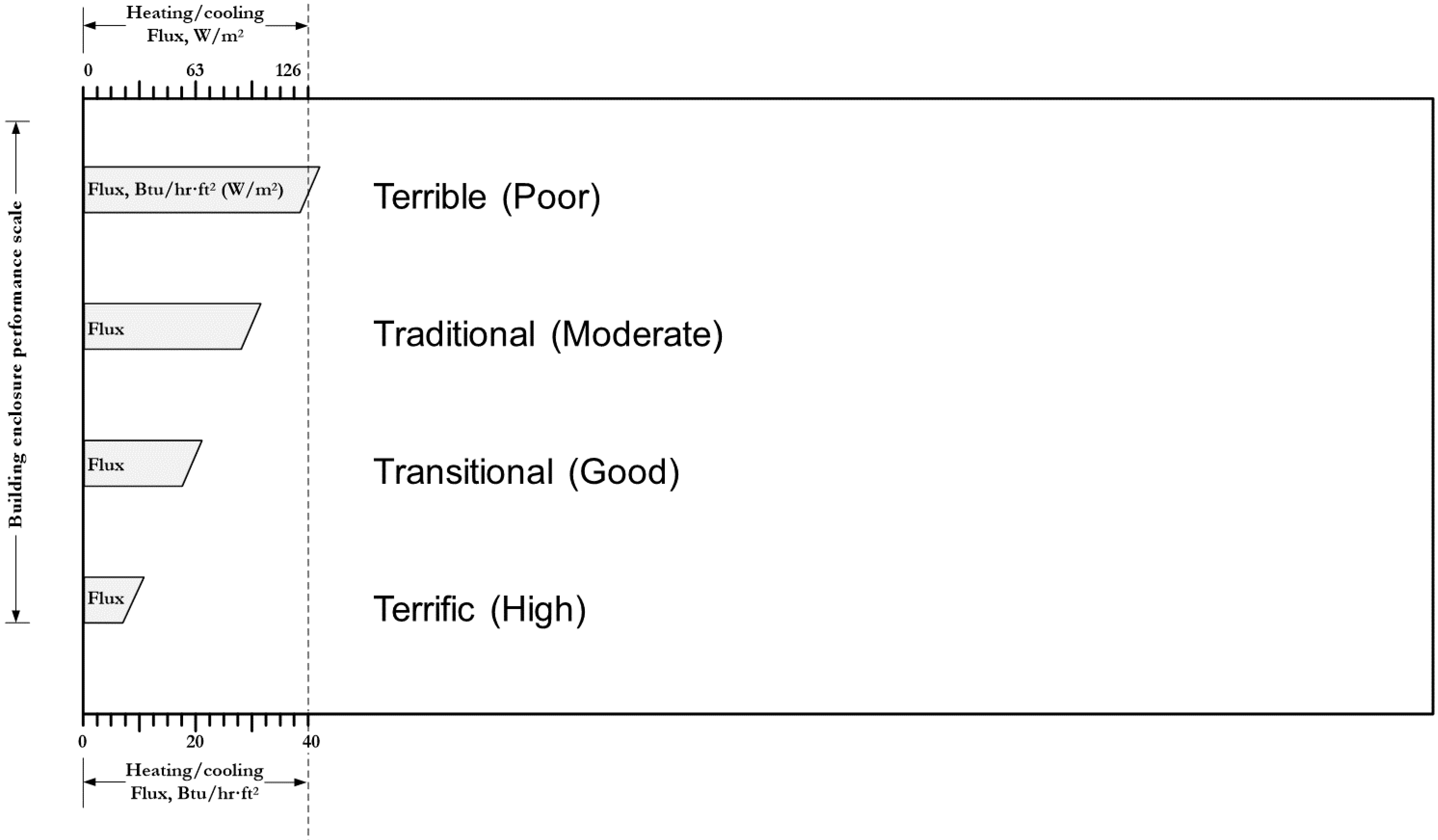
sustainability: risk to society when conservation is the exclusive goal.

The Interaction & Connection between Buildings, HVAC System & Indoor Environmental Quality



Source: Bean, R. The Interaction and Connection between Buildings, HVAC System, and Indoor Environmental Quality. ASHRAE IAQ2013, Conference Proceedings. Vancouver, October, 2013

The Interaction & Connection between Buildings, HVAC System & Indoor Environmental Quality



Source: Bean, R. The Interaction and Connection between Buildings, HVAC System, and Indoor Environmental Quality. ASHRAE IAQ2013, Conference Proceedings. Vancouver, October, 2013

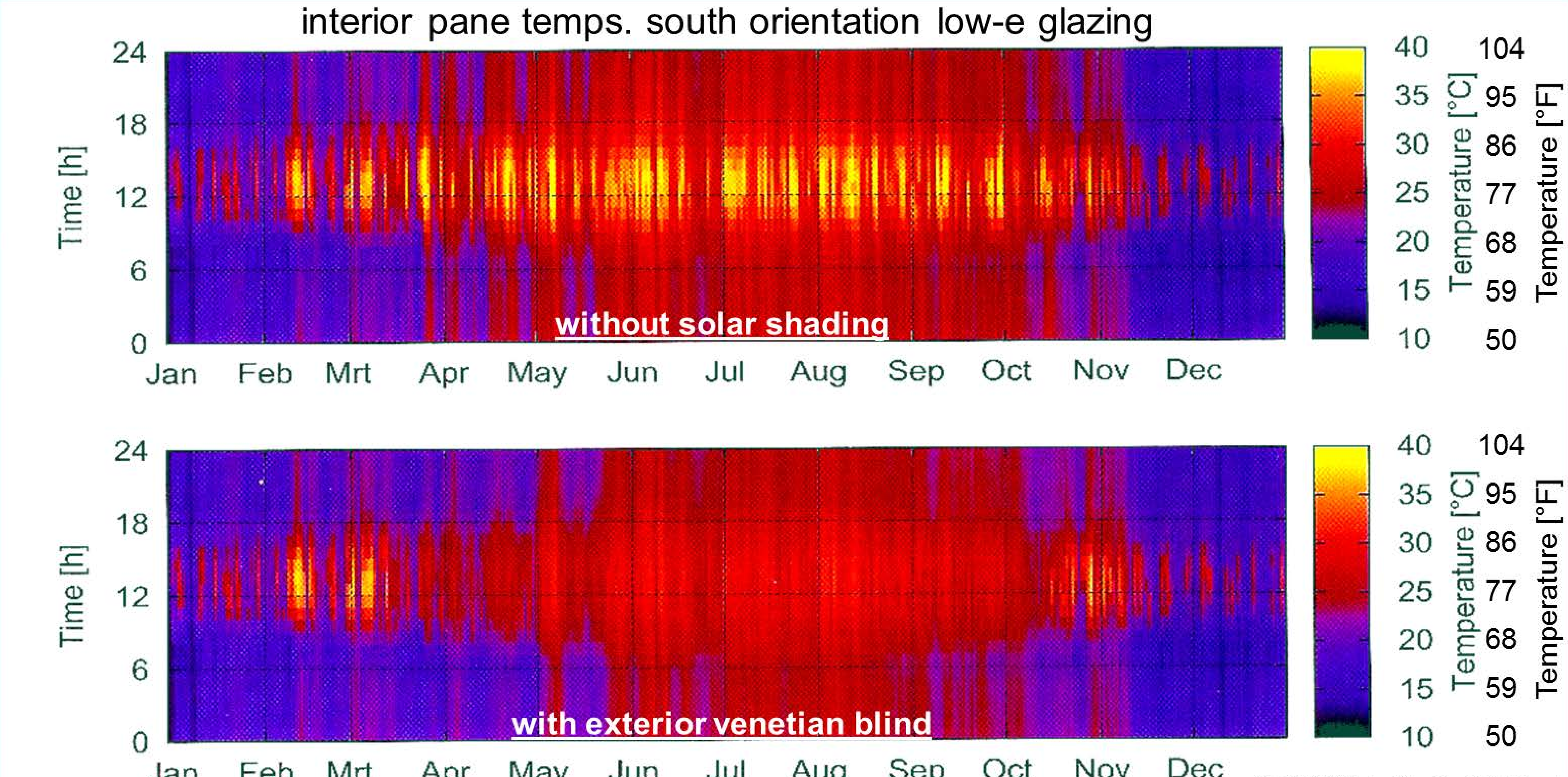
the graph – section 1

building performance, flux,

HVAC exchanger surface areas

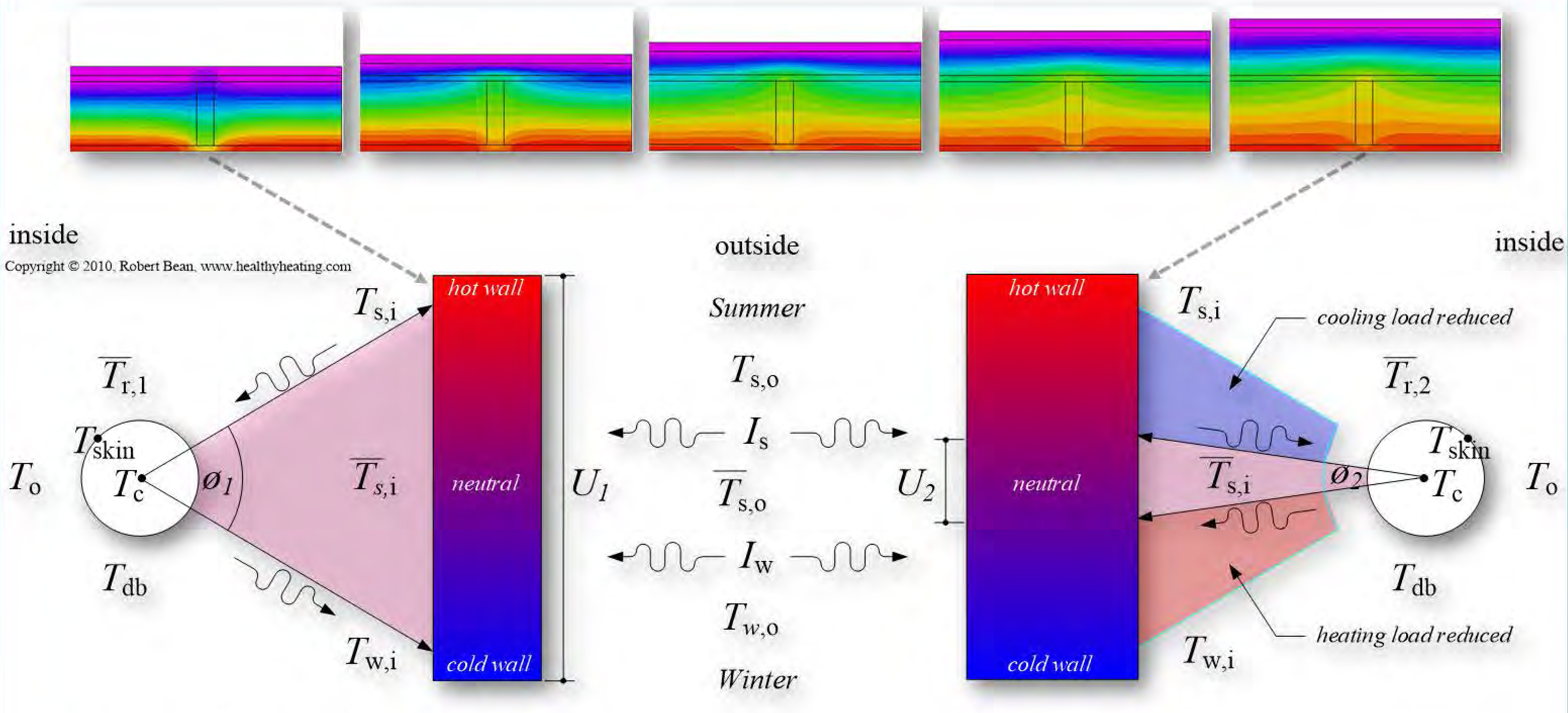
& temperatures.

building performance



source/credit: REHVA Solar Shading Guidebook

building performance

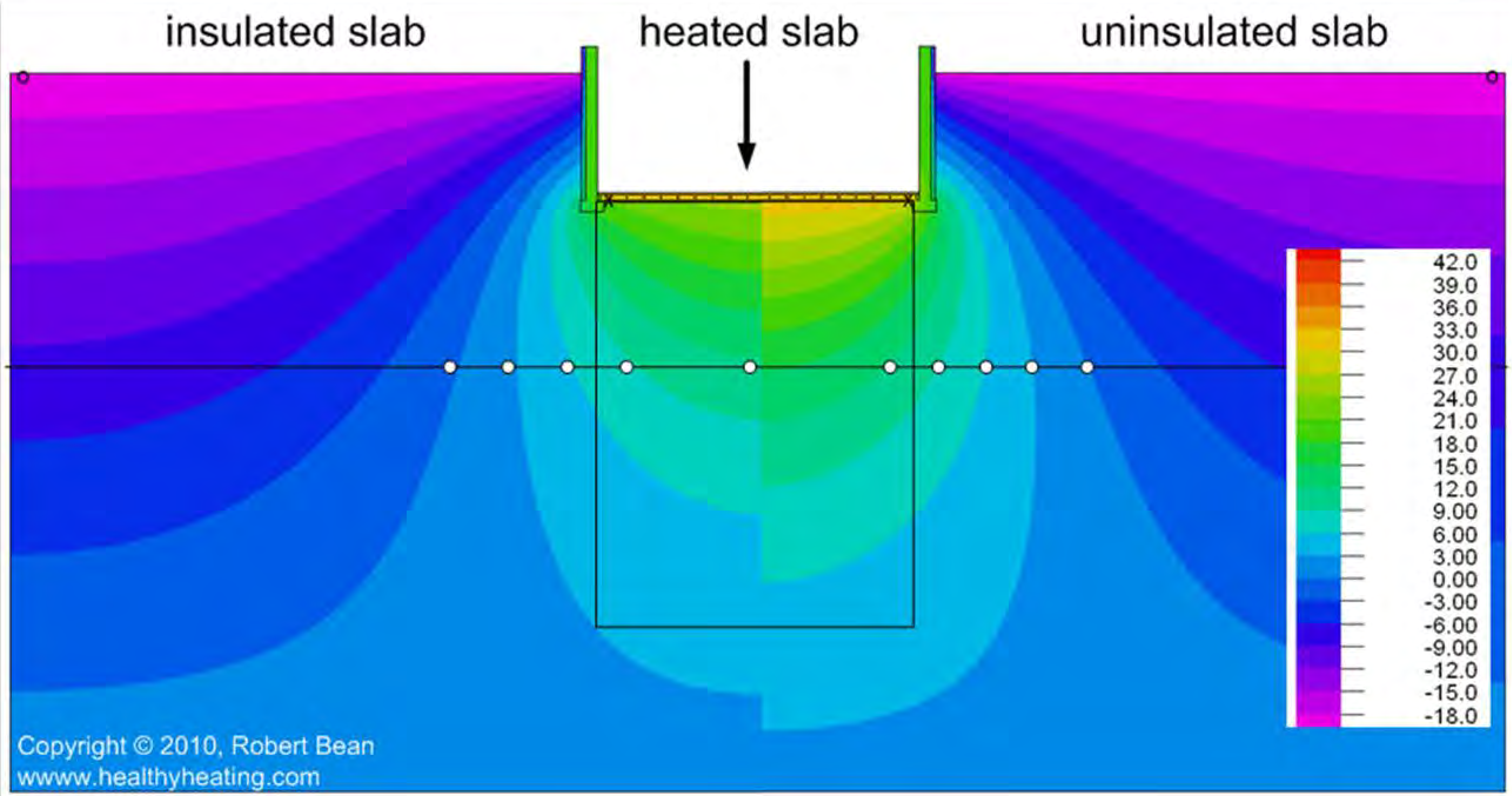


a) Poor performing enclosure

b) Good performing enclosure

building performance

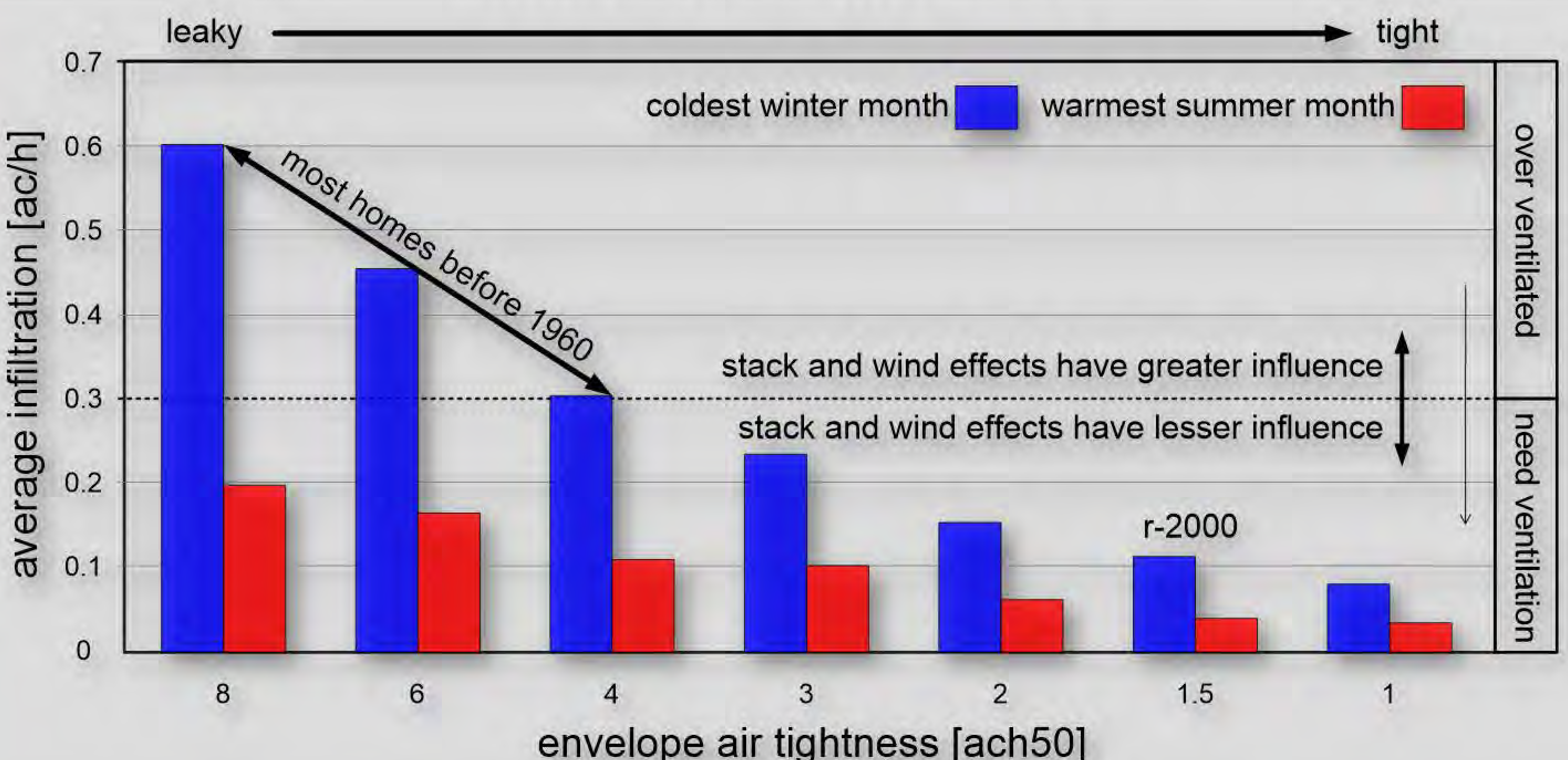
soil thermal conductivities – should slabs be insulated?



building performance

source/credit: NRC/CMHC

infiltration/exfiltration



fluxes…are a changing

cold to very cold climates

terrible
- built to code
- > 30 Btu/hr/sf
- >6ACH50
- 160°F-180°F

traditional
- built to code
- 20-30 Btu/hr/sf
- 6-4ACH50
- 160°F-140°F

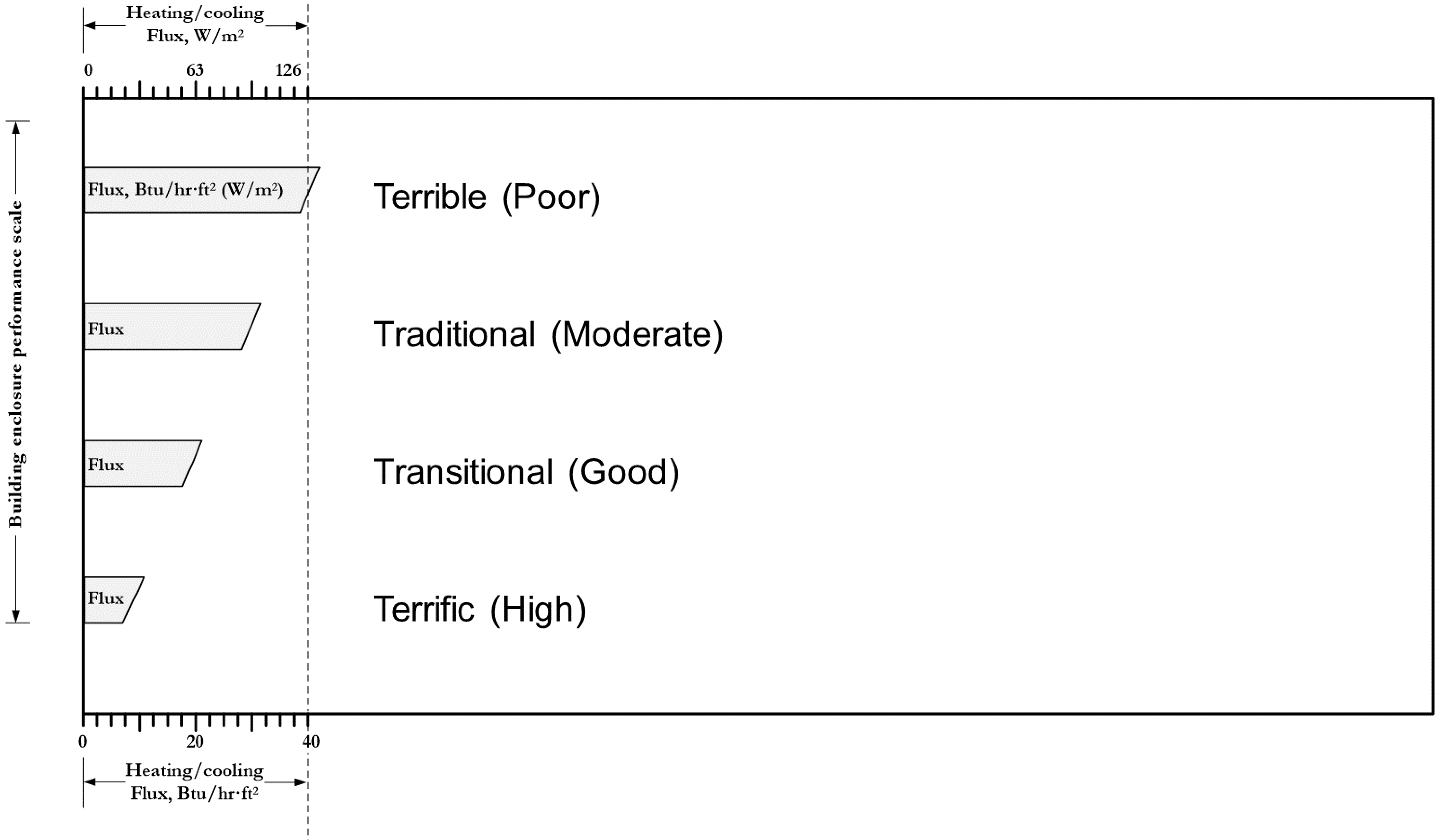
transitional
- above code
- 10-20 Btu/hr/sf
- 4-2ACH50
- 140°F-100°F

terrific
- future codes
- <10 Btu/hr/sf
- <2ACH50
- < 100°F

the dinner rule applies to efficiency: take what you need but use what you take

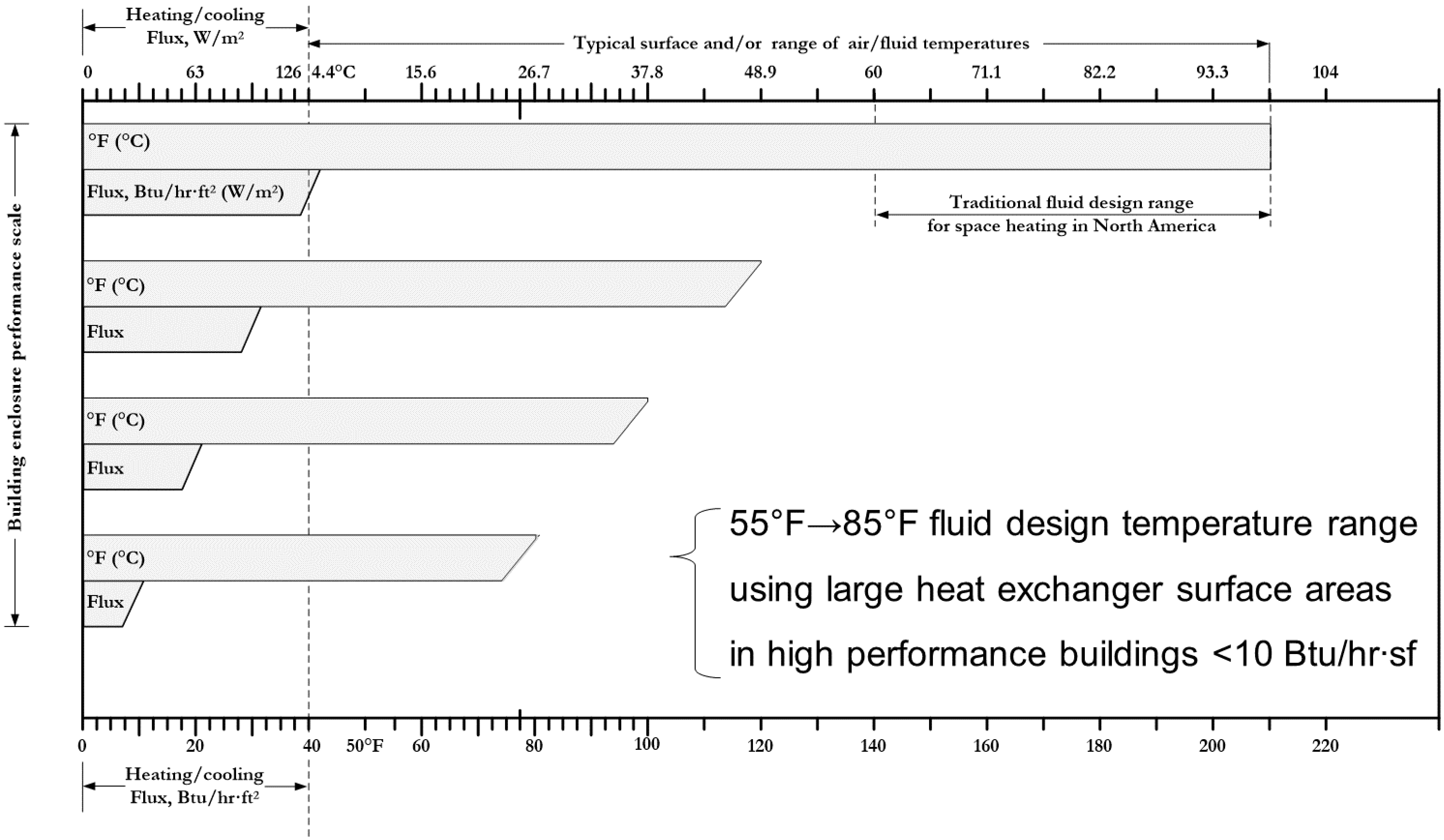
the hammer rule applies to temperature: a sledge hammer isn’t needed for finishing nails

The Interaction & Connection between Buildings, HVAC System & Indoor Environmental Quality



Source: Bean, R. The Interaction and Connection between Buildings, HVAC System, and Indoor Environmental Quality. ASHRAE IAQ2013, Conference Proceedings. Vancouver, October, 2013

The Interaction & Connection between Buildings, HVAC System & Indoor Environmental Quality



Source: Bean, R. The Interaction and Connection between Buildings, HVAC System, and Indoor Environmental Quality. ASHRAE IAQ2013, Conference Proceedings. Vancouver, October, 2013

the graph – section 2

heat exchanger surface areas,

operating temperatures and plant

efficiencies

exchanger surface area matters

temperature: heat transfer 101

$$q = U \cdot A \cdot \Delta T_{lm}{}^{n}$$

where;

q = thermal power transferred, Btu/hr, (W)

U = coefficient of heat transfer, Btu/hr/sf/°F (W/m^2K)

determined by experiment or by calculation

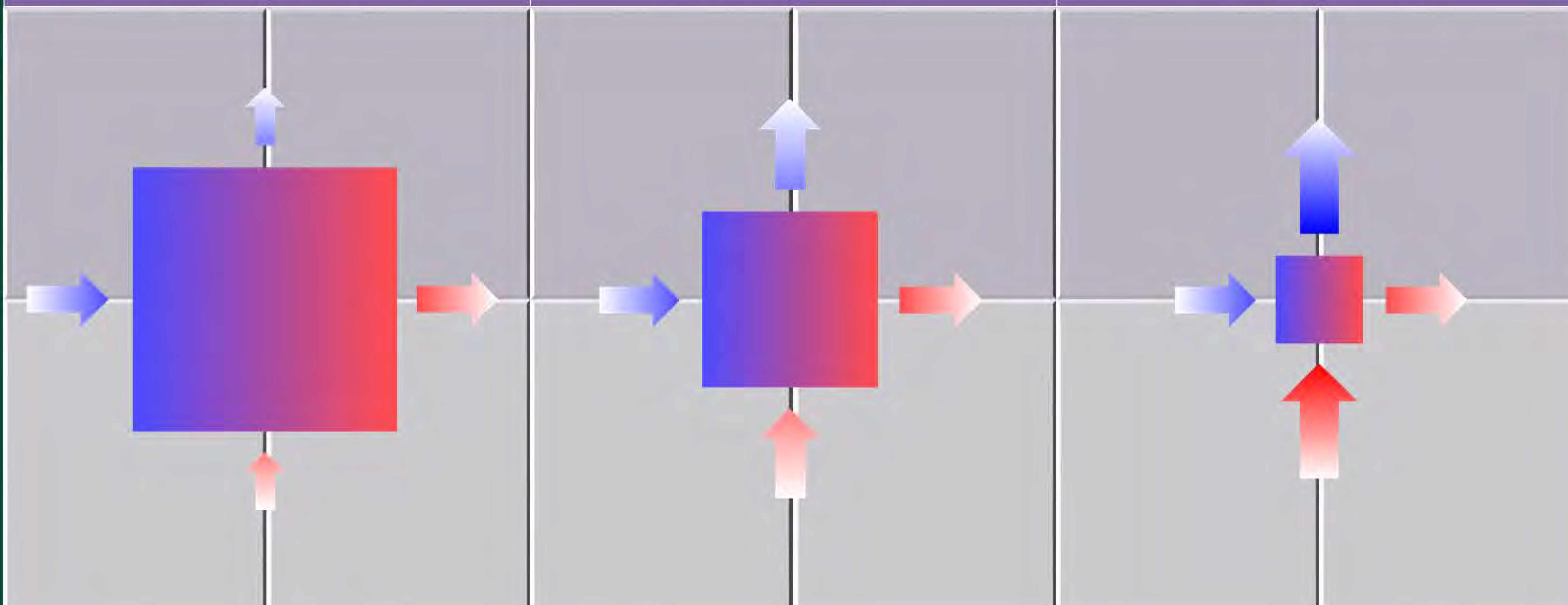
A = surface area of the heat transfer component, $ft^{2,}$ (m^2)

ΔT_{lm} = log mean temperature difference between the hot and the cold medium, °F (K)

n = power exponent – empirical values through testing

exchanger surface area matters

high cooling/low heating temps. heat exchangers large surface area range 55°F – 100°F	medium temperature heat exchangers med. surface area range 50°F - 150°F	low cool - high heat temperature heat exchangers small surface area range 45°F - 180°F

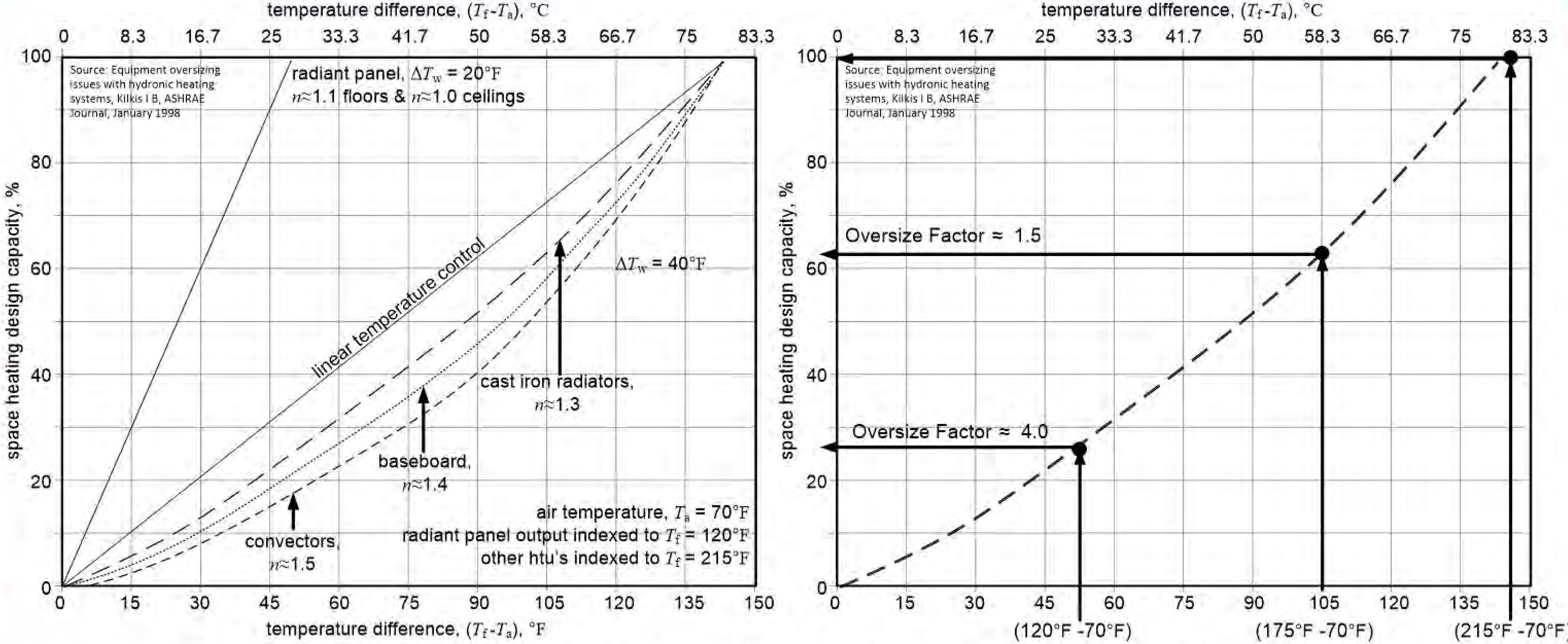


supply and return temperatures matter

effectiveness coefficient, (ϕ) for temperatures in various countries where t_{is} = 20°C (68°F)					
ranked by largest Δt and lowest t_s	supply, t_s		return, t_r		$\phi = \frac{t_s - t_r}{t_s - t_{is}}$
	°C	°F	°C	°F	
Denmark	70	158	40	104	0.60
Finland	70	158	40	104	0.60
Korea	70	158	50	122	0.40
Germany	80	176	60	140	0.33
Romania	95	203	75	167	0.27
Russia	95	203	75	167	0.27
Poland	85	185	71	160	0.22
United Kingdom	82	180	70	158	0.19
North America	82	180	70	158	0.19

source: skagestad, b., mildenstein, p., district heating and cooling connection handbook, international energy agency, 2009

oversized HEX surface areas lead to lower temps

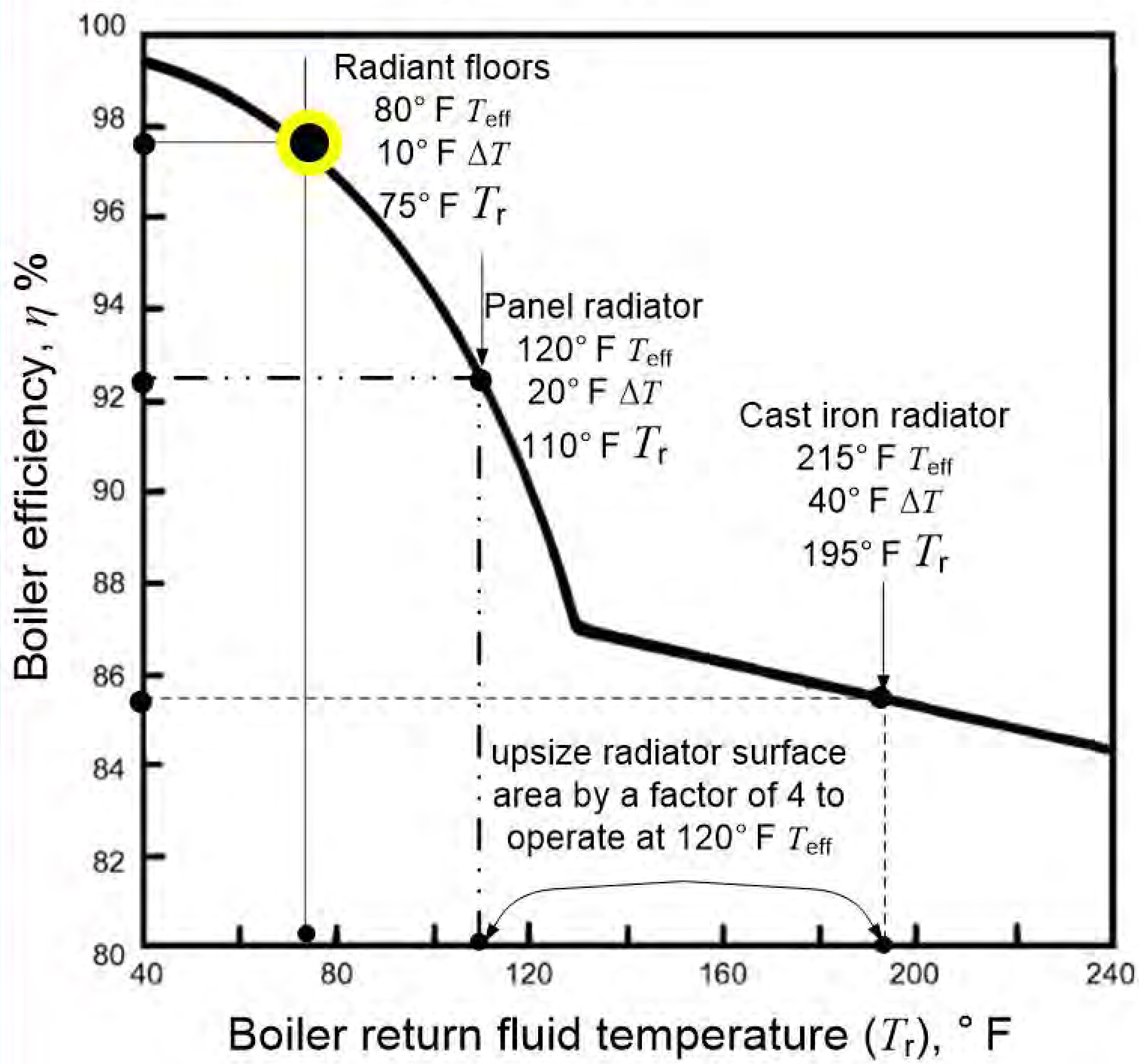


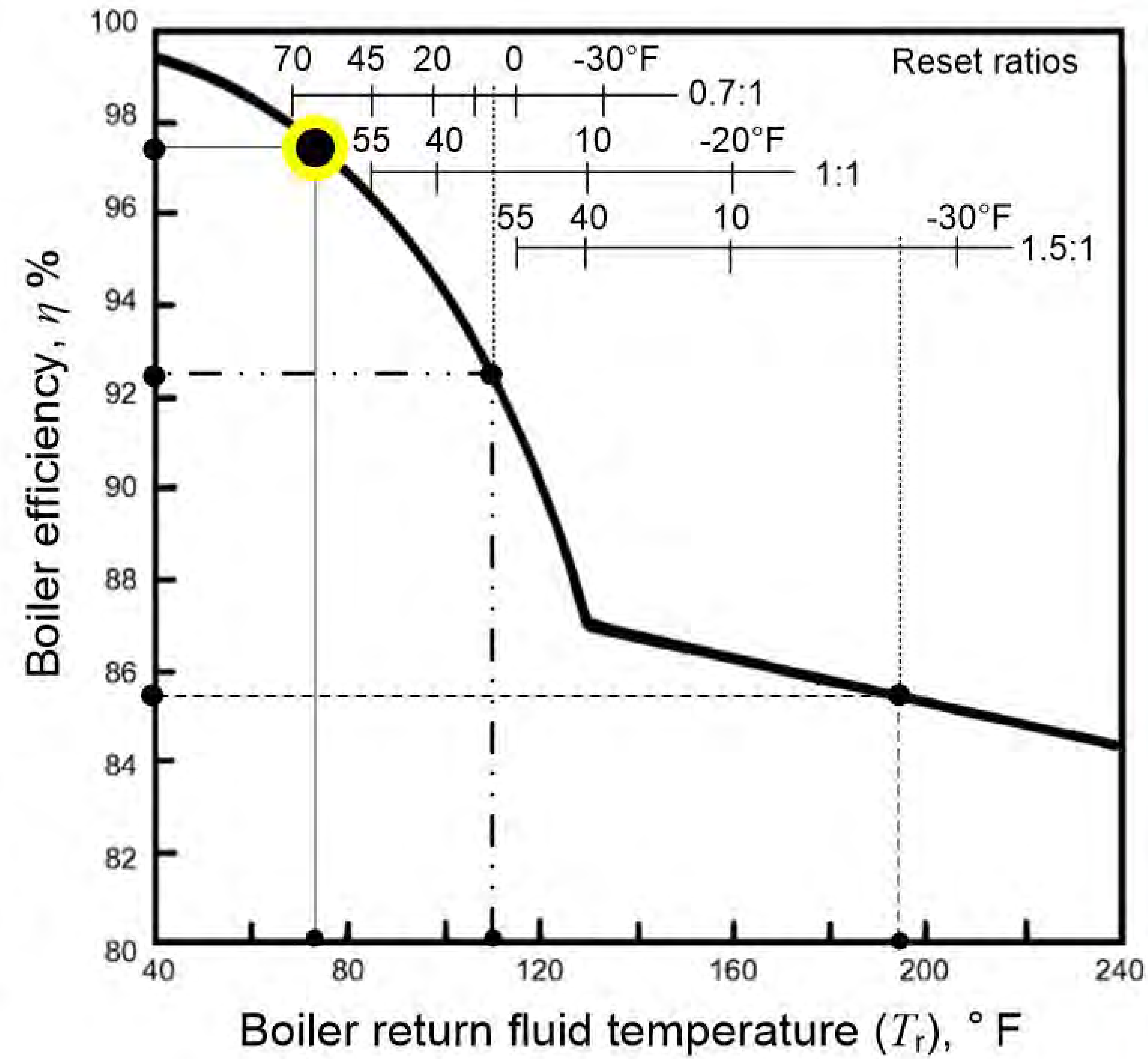
example: oversize factor, OF = $[(215°F - 70°F)/(175°F - 70°F)]^{1.3} = 1.5$

if the cast iron radiator were to run at the 120 F reference temperature for panel radiators, it would have to oversized by a factor of 4 to deliver 100% capacity at design conditions...if the effective temperature is reduced there will be a corresponding reduction in the capacity, i.e. at 180 F the capacity of the system would be reduced to 63% of its design capacity and thus would have to be oversized by a factor of 2.6

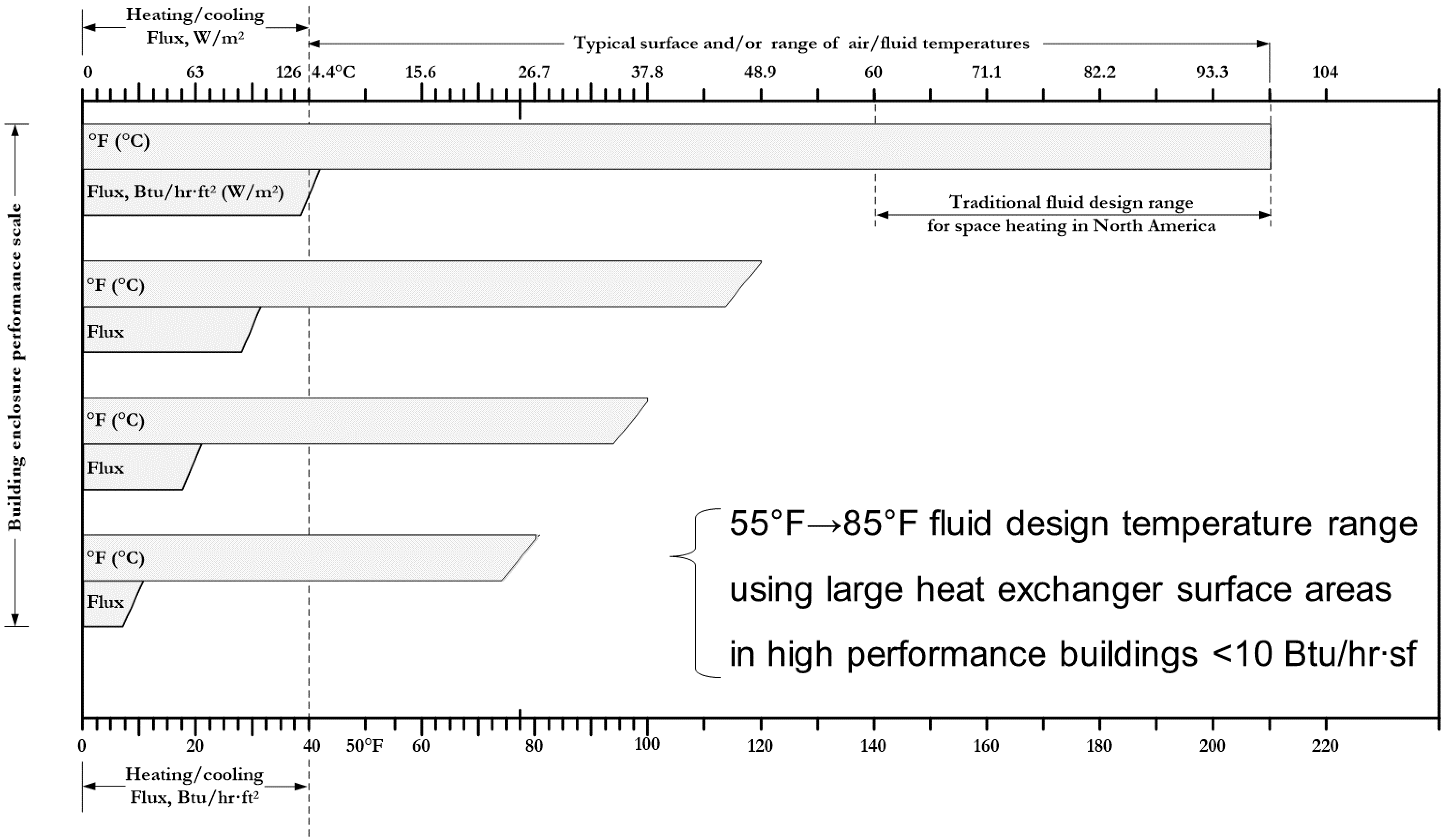
lower temps = higher efficiency

source/credit/adapted: ASHRAE Systems and Equipment Handbook





The Interaction & Connection between Buildings, HVAC System & Indoor Environmental Quality



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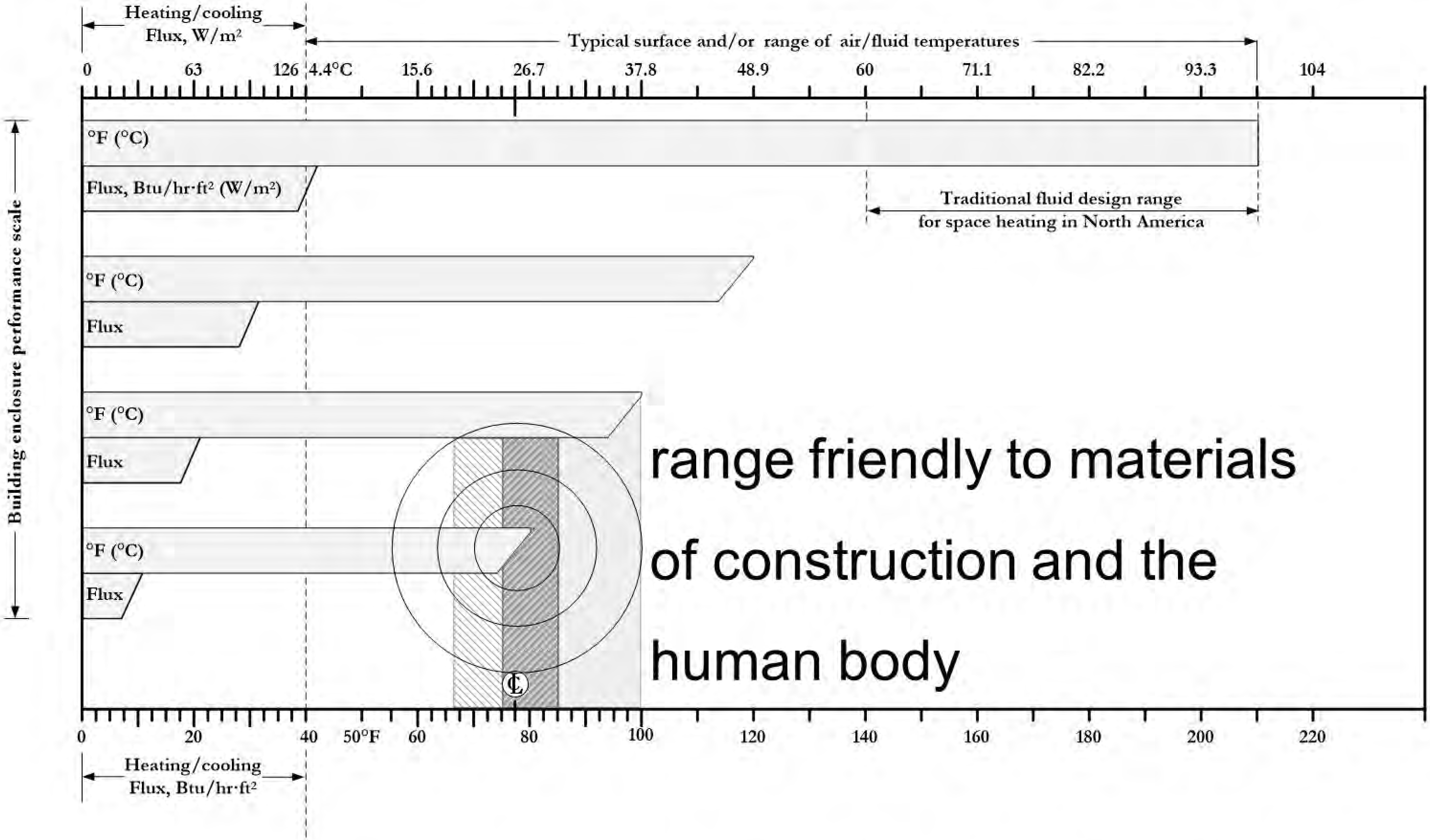
The Interaction & Connection between Buildings, HVAC System & Indoor Environmental Quality

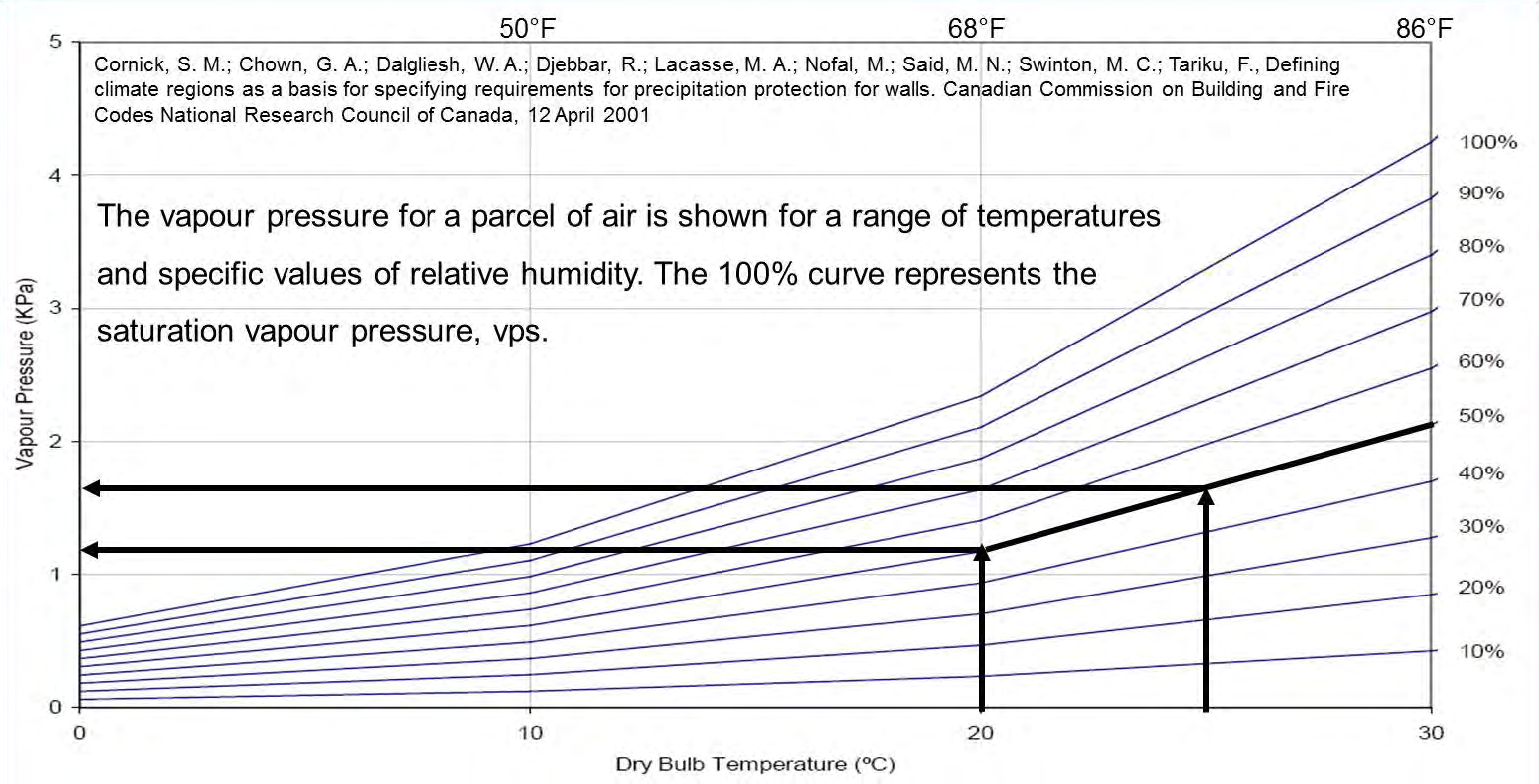


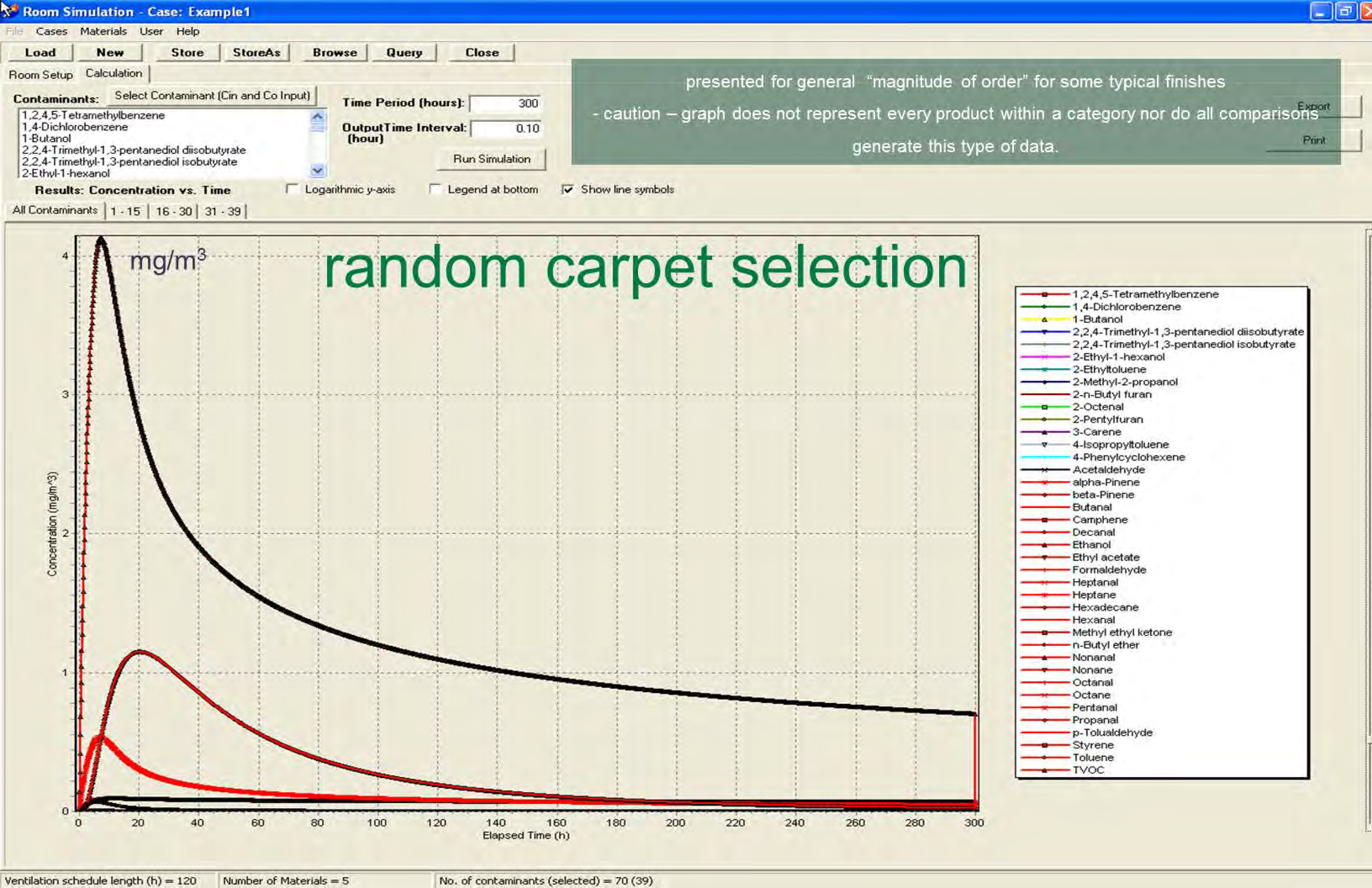
Source: Bean, R. The Interaction and Connection between Buildings, HVAC System, and Indoor Environmental Quality. ASHRAE IAQ2013, Conference Proceedings. Vancouver, October, 2013

the graph – section 3

temperature, moisture and the indoor environment

temperature and moisture





Room Simulation - Case: Example1
File Cases Materials User Help
Load New Store StoreAs Browse Query Close
Room Setup Calculation
presented for general "magnitude of order" for some typical finishes
- caution – graph does not represent every product within a category nor do all comparisons generate this type of data.
Export
Print
Contaminants: Select Contaminant (Cin and Co Input)
1,2,4,5-Tetramethylbenzene
1,4-Dichlorobenzene
1-Butanol
2,2,4-Trimethyl-1,3-pentanediol diisobutyrate
2,2,4-Trimethyl-1,3-pentanediol isobutyrate
2-Ethyl-1-hexanol
Time Period (hours): 300
OutputTime Interval: (hour) 0.10
Run Simulation
Results: Concentration vs. Time
Logarithmic y-axis
Legend at bottom
Show line symbols
All Contaminants
1 - 15
16 - 30
31 - 39
mg/m3
random carpet selection
Concentration (mg/m^3)
Elapsed Time (h)
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
0 1 2 3 4
1,2,4,5-Tetramethylbenzene
1,4-Dichlorobenzene
1-Butanol
2,2,4-Trimethyl-1,3-pentanediol diisobutyrate
2,2,4-Trimethyl-1,3-pentanediol isobutyrate
2-Ethyl-1-hexanol
2-Ethyltoluene
2-Methyl-2-propanol
2-n-Butyl furan
2-Octenal
2-Pentylfuran
3-Carene
4-Isopropyltoluene
4-Phenylcyclohexene
Acetaldehyde
alpha-Pinene
beta-Pinene
Butanal
Camphene
Decanal
Ethanol
Ethyl acetate
Formaldehyde
Heptanal
Heptane
Hexadecane
Hexanal
Methyl ethyl ketone
n-Butyl ether
Nonanal
Nonane
Octanal
Octane
Pentanal
Propanal
p-Tolualdehyde
Styrene
Toluene
TVOC
Ventilation schedule length (h) = 120
Number of Materials = 5
No. of contaminants (selected) = 70 (39)

temperature and moisture

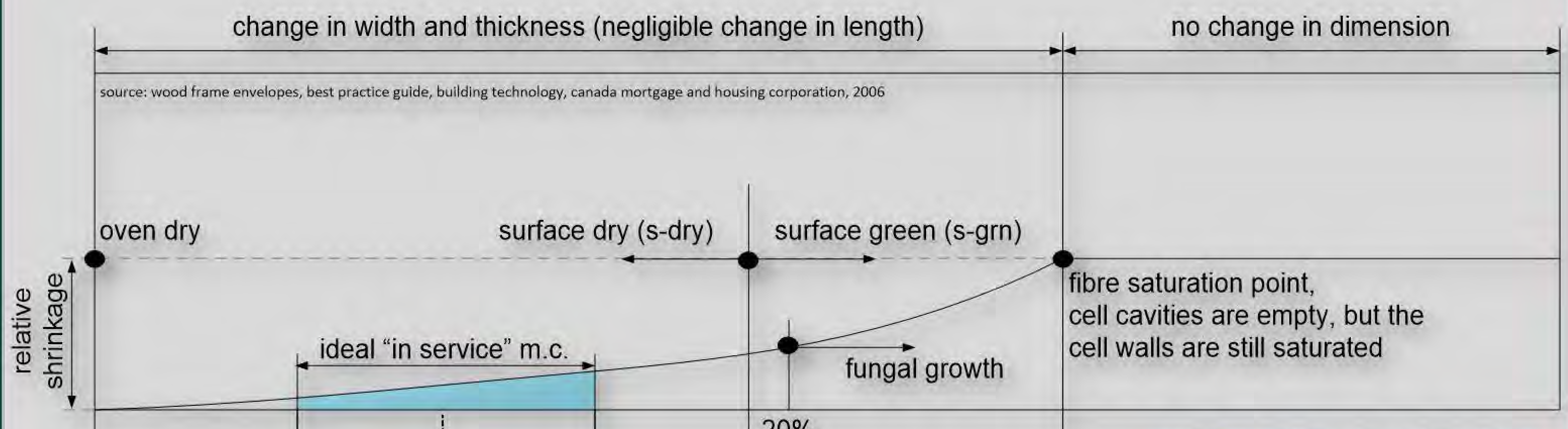
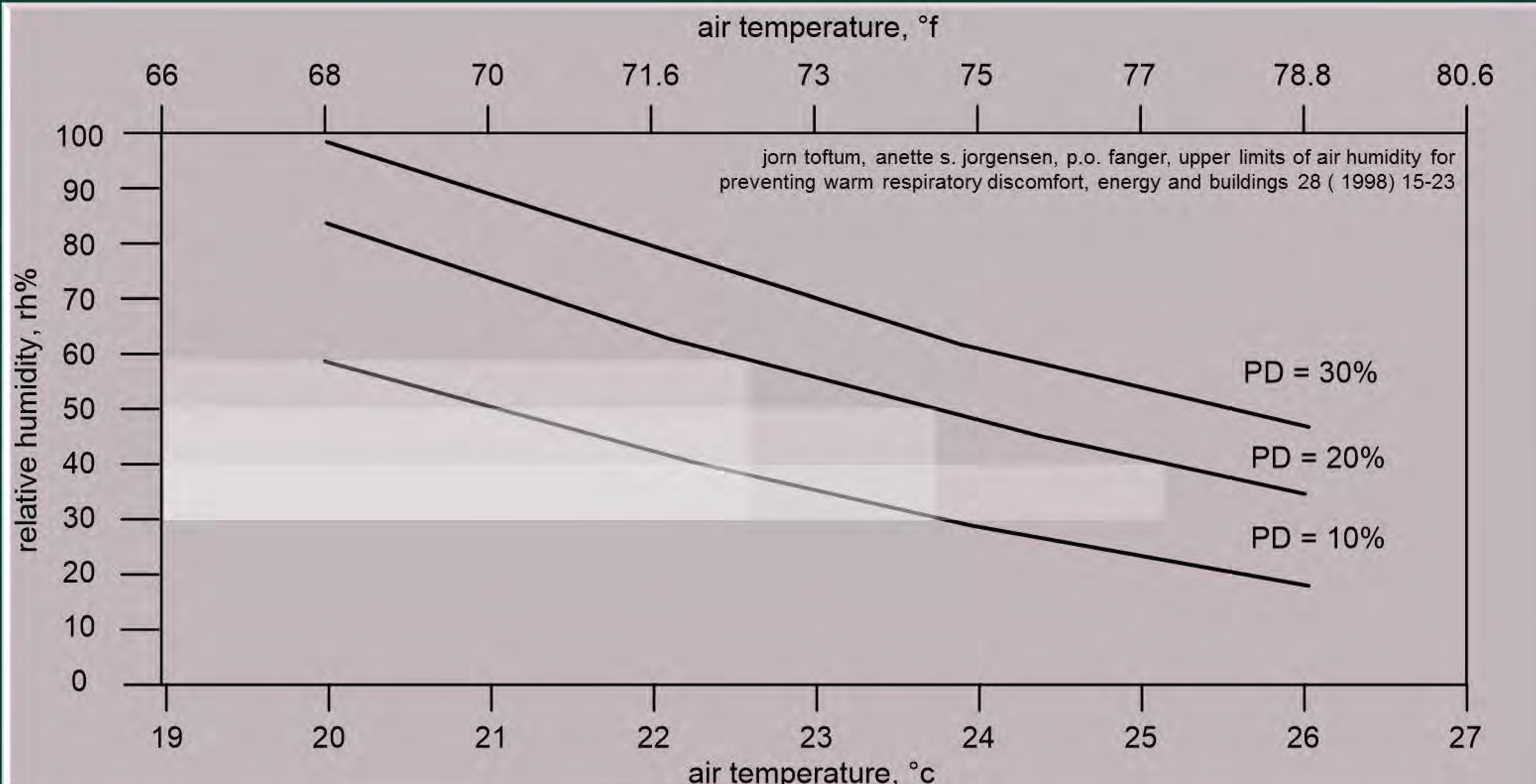
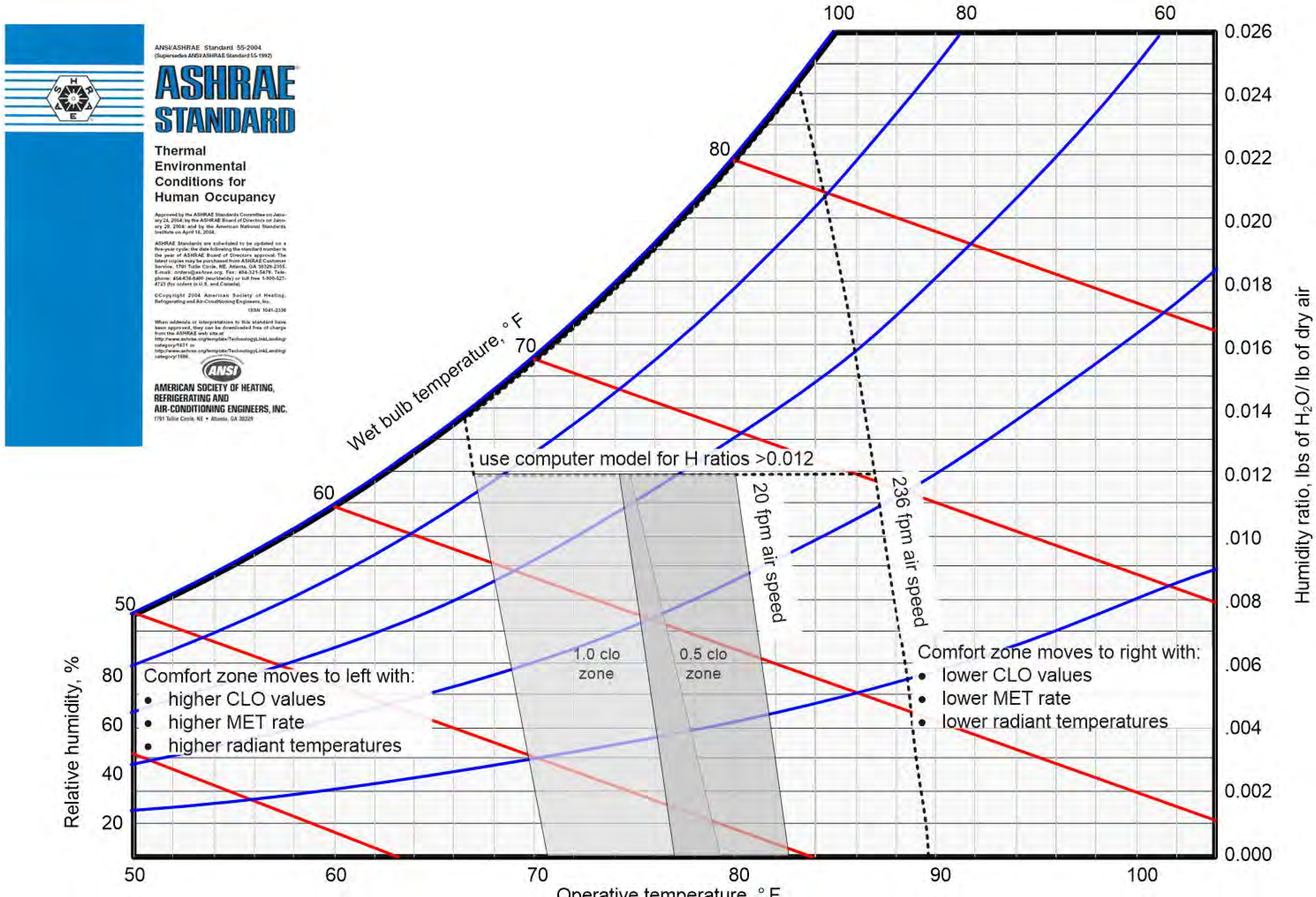


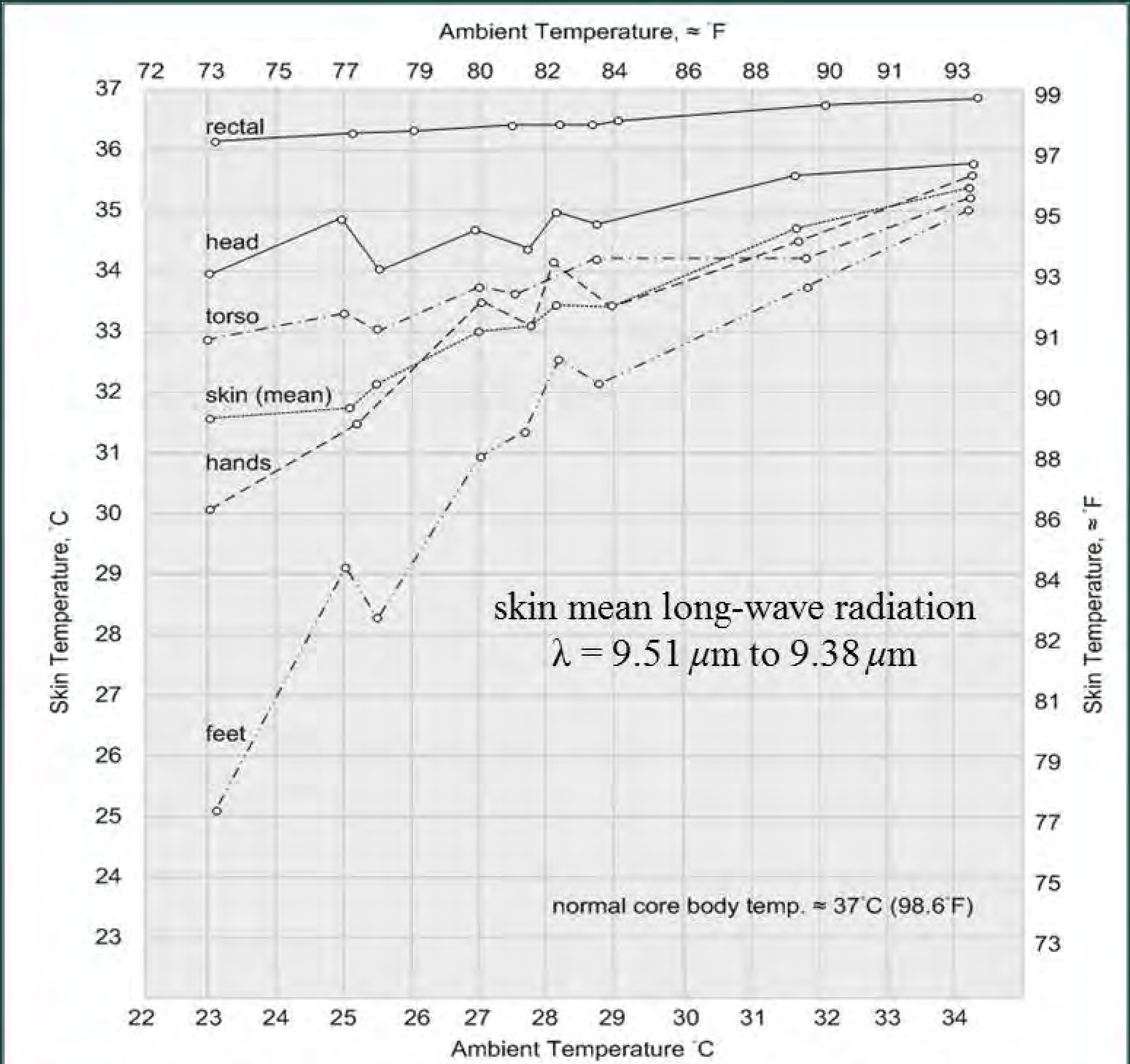
photo credit/source: power and syred/science photo library

temperature and moisture




ANSI/ASHRAE Standard 55-2004
(Supersedes ANSI/ASHRAE Standard 55-1992)
ASHRAE STANDARD
Thermal Environmental Conditions for Human Occupancy
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
100
80
60
0.026
0.024
0.022
0.020
0.018
0.016
0.014
0.012
.010
.008
.006
.004
0.002
0.000
Humidity ratio, lbs of H_2O/ lb of dry air
Wet bulb temperature, ° F
80
70
60
50
use computer model for H ratios >0.012
20 fpm air speed
236 fpm air speed
1.0 clo zone
0.5 clo zone
Comfort zone moves to left with:
• higher CLO values
• higher MET rate
• higher radiant temperatures
Comfort zone moves to right with:
• lower CLO values
• lower MET rate
• lower radiant temperatures
Relative humidity, %
80
60
40
20
50
60
70
80
90
100
Operative temperature, ° F

temperature and moisture



Skin temperatures on different parts of a nude person measured at different ambient temperatures
Adapted from: Olesen, B.W., 1982, Thermal Comfort, Technical Review, Bruel & Kjaer

body heat from a localized surface is suppressed when,

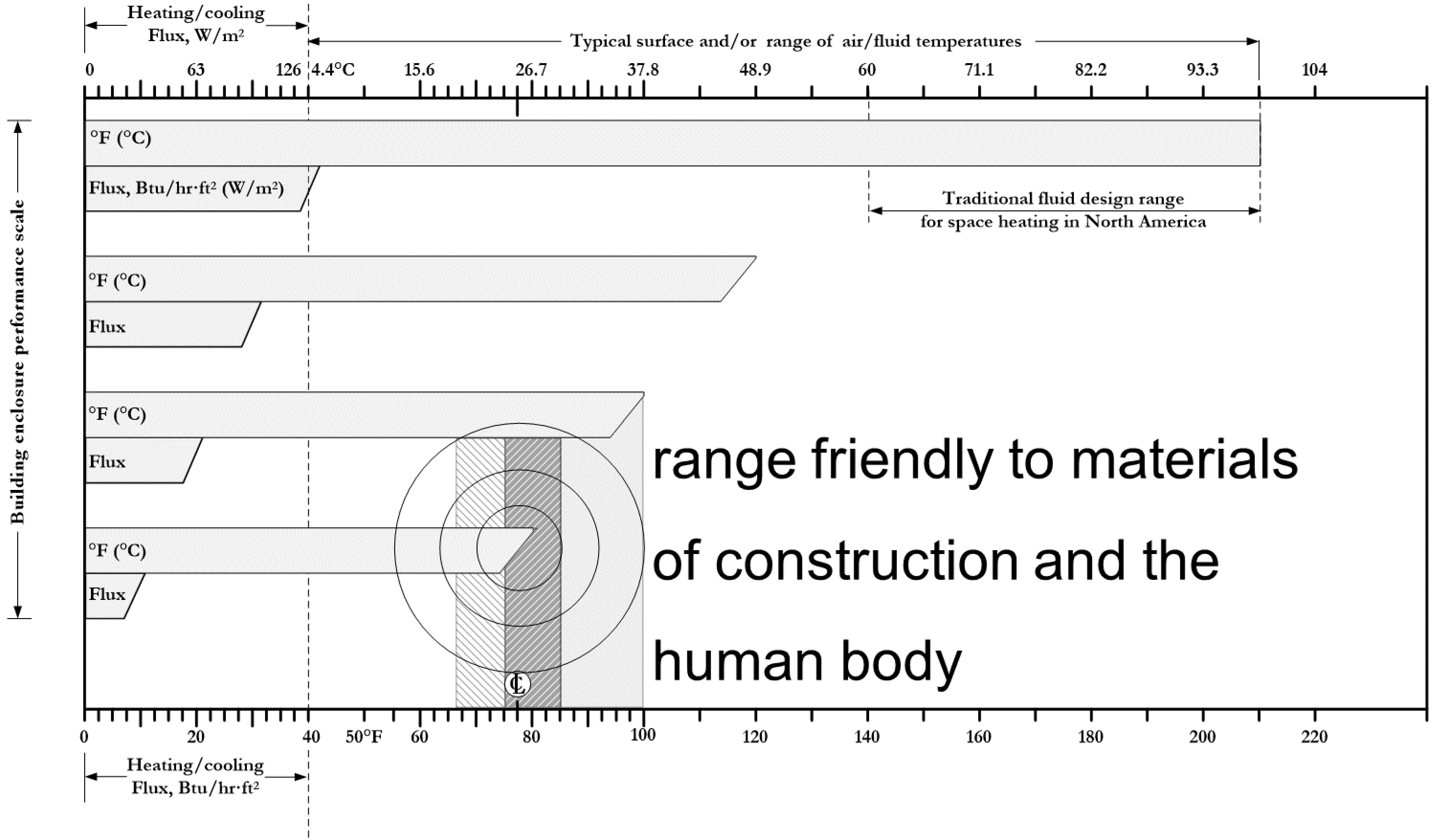
$$t_{skin,\ local} < t_{s,n}\ \&\ t_{mr}$$

body heat from a localized surface is activated when

$$t_{s,n}\ \&\ t_{mr} < t_{skin,\ local}$$

skin temperatures on different parts of a nude person measured at different ambient temperatures, adapted from: olesen, b.w., thermal comfort, technical review, bruel & kjaer, 1982

The Interaction & Connection between Buildings, HVAC System & Indoor Environmental Quality



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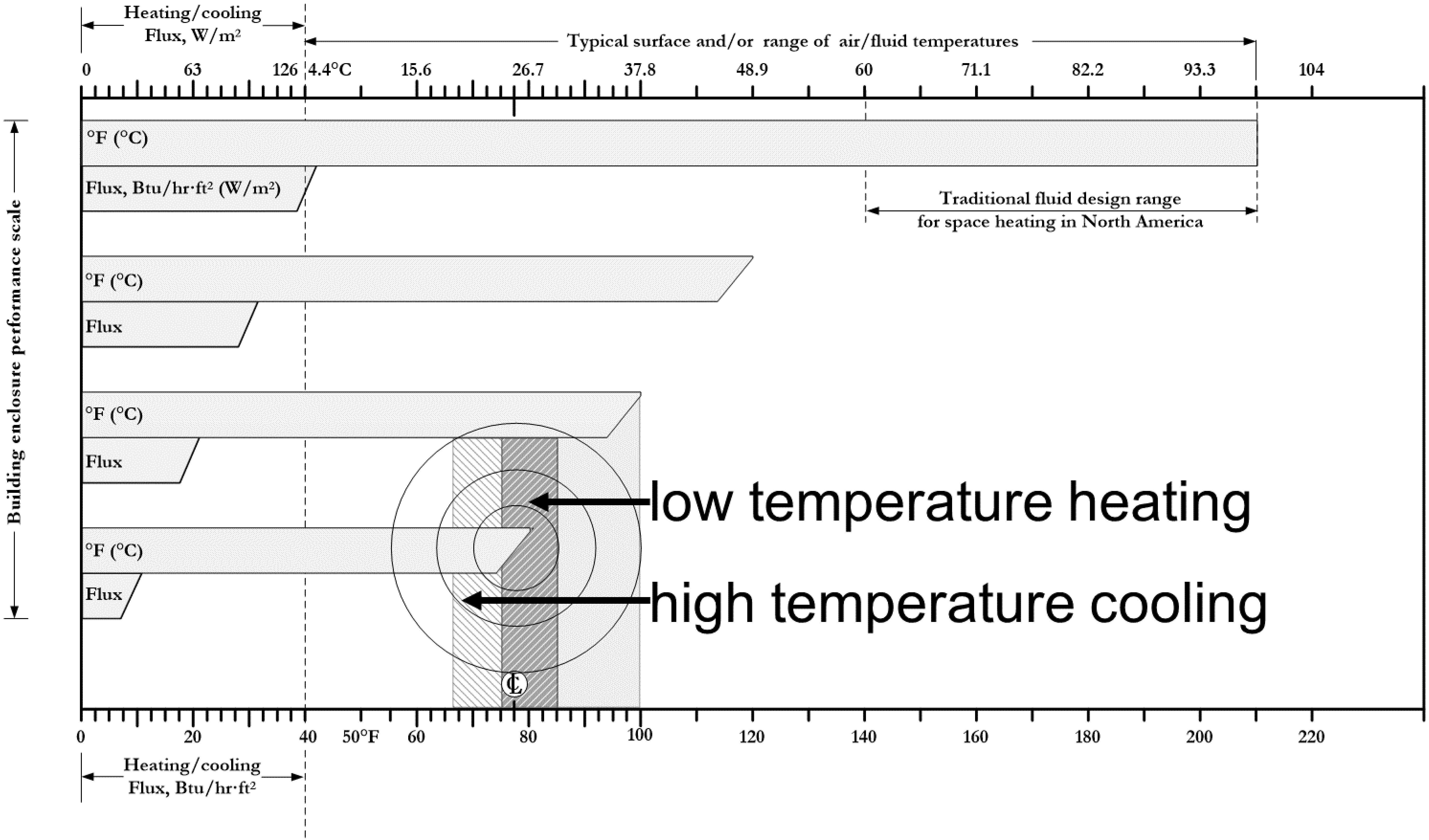
The Interaction & Connection between Buildings, HVAC System & Indoor Environmental Quality



Source: Bean, R. The Interaction and Connection between Buildings, HVAC System, and Indoor Environmental Quality. ASHRAE IAQ2013, Conference Proceedings. Vancouver, October, 2013

the graph – section 4

low temperature heating

and

high temperature cooling.

low temp heating / high temp cooling

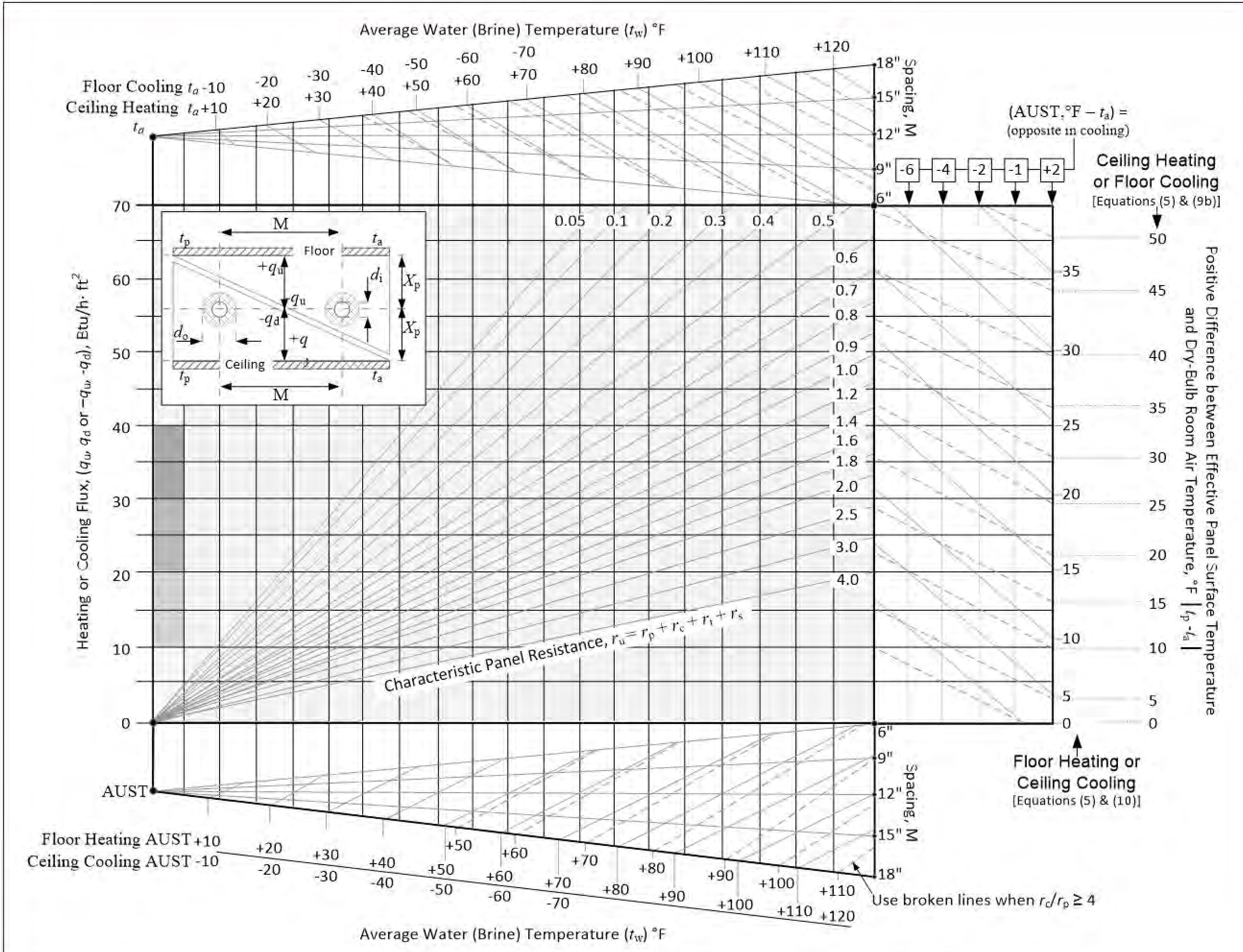


Fig. 9 Design Graph for Heating and Cooling with Floor and Ceiling Panels, Panel Heating and Cooling 6.9, Reprinted With Permission, 2000 ASHRAE Systems and Equipment Handbook, www.ASHRAE.org.

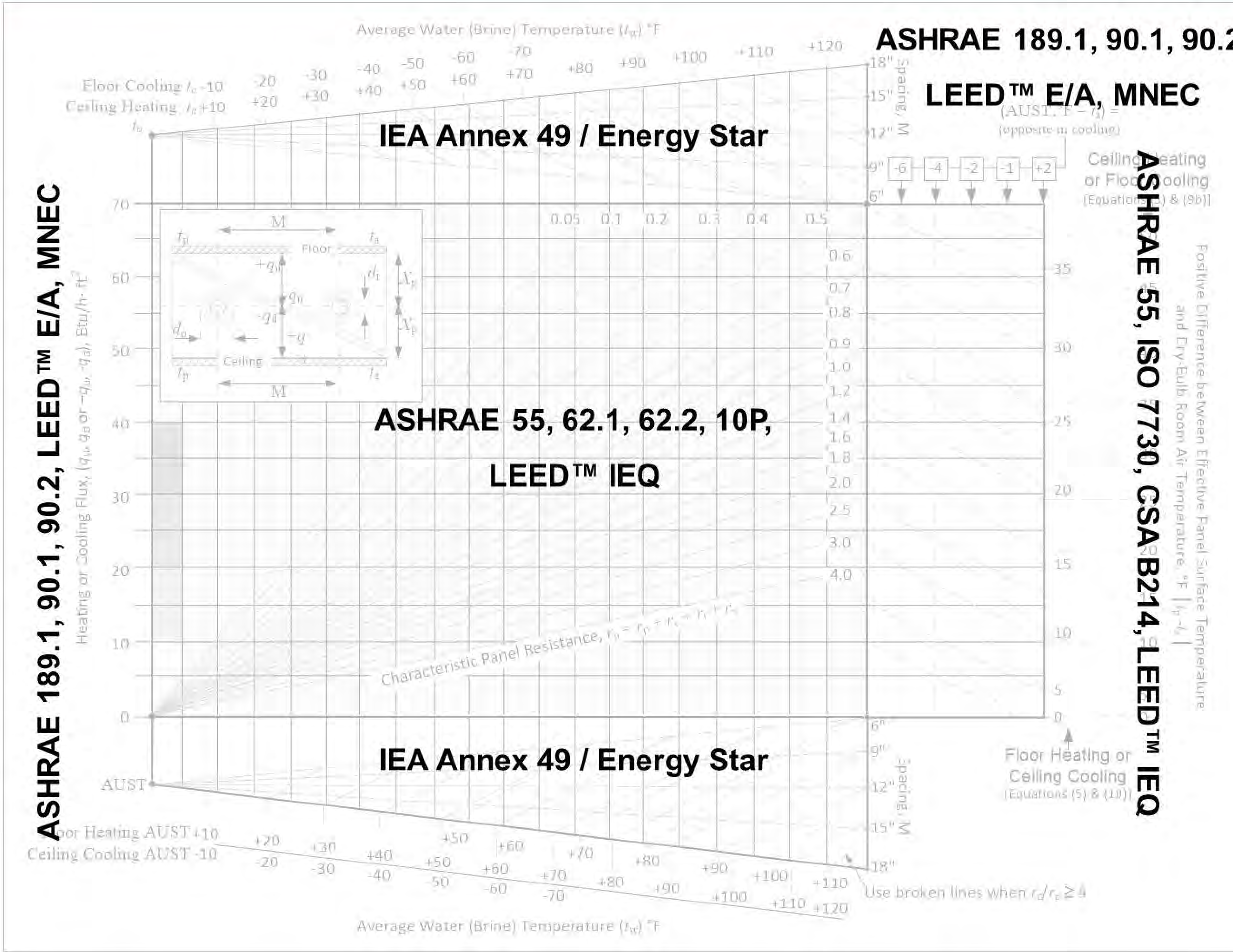


Fig. 9 Design Graph for Heating and Cooling with Floor and Ceiling Panels, Panel Heating and Cooling 6.9, Reprinted With Permission, 2000 ASHRAE Systems and Equipment Handbook, www.ASHRAE.org.

$$\overline{t_w} = \text{AUST} + 25°F = 70°F + 25°F = 95°F$$

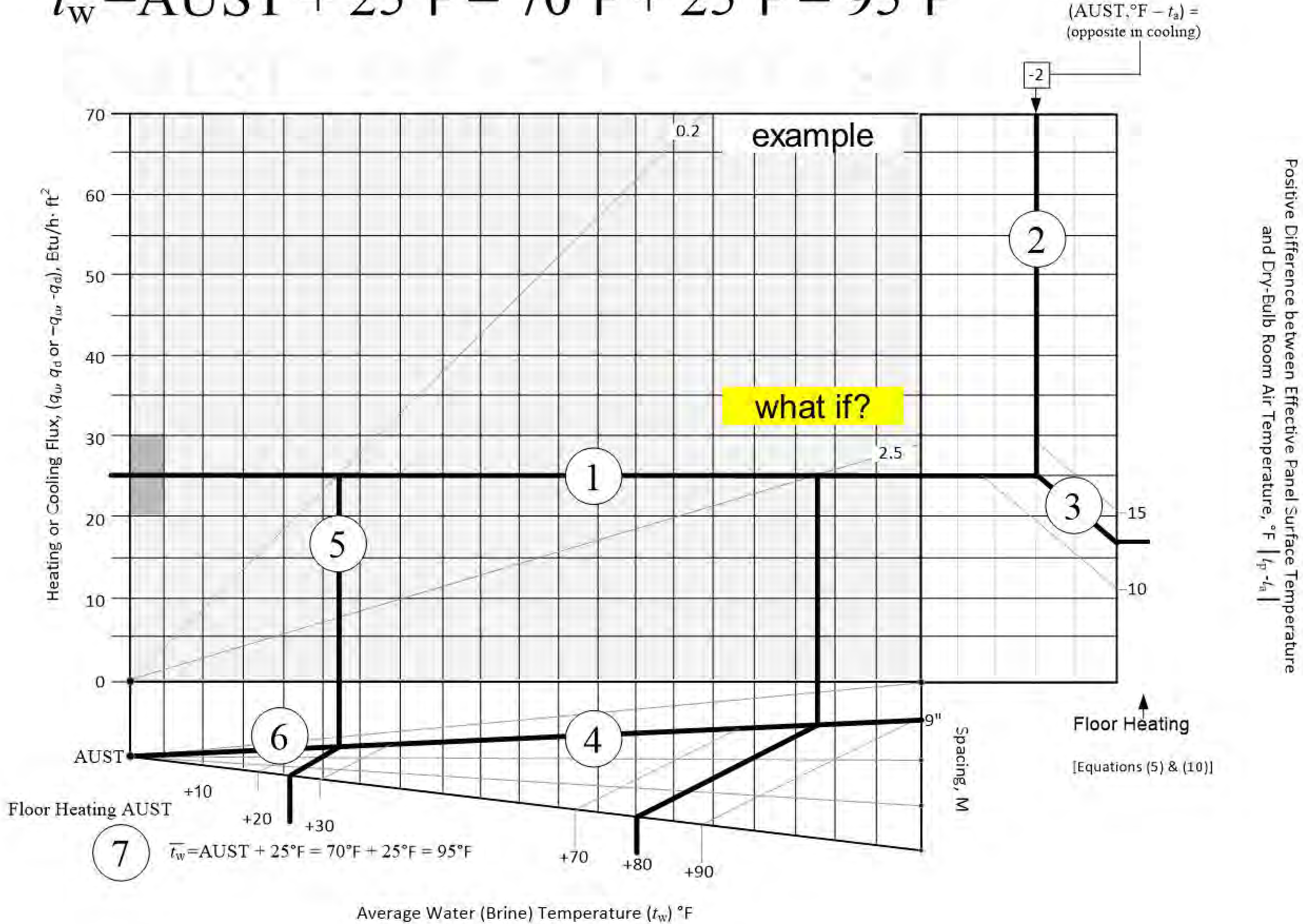


Fig. 9 Design Graph for Heating and Cooling with Floor and Ceiling Panels, Panel Heating and Cooling 6.9, Reprinted With Permission, 2000 ASHRAE Systems and Equipment Handbook, www.ASHRAE.org.

$\overline{t_w}$=AUST + 80°F = 70°F + 80°F = 150°F

$\overline{t_w}$=AUST + 25°F = 70°F + 25°F = 95°F

$\overline{t_w}$=AUST + 10°F = 70°F + 10°F = 80°F

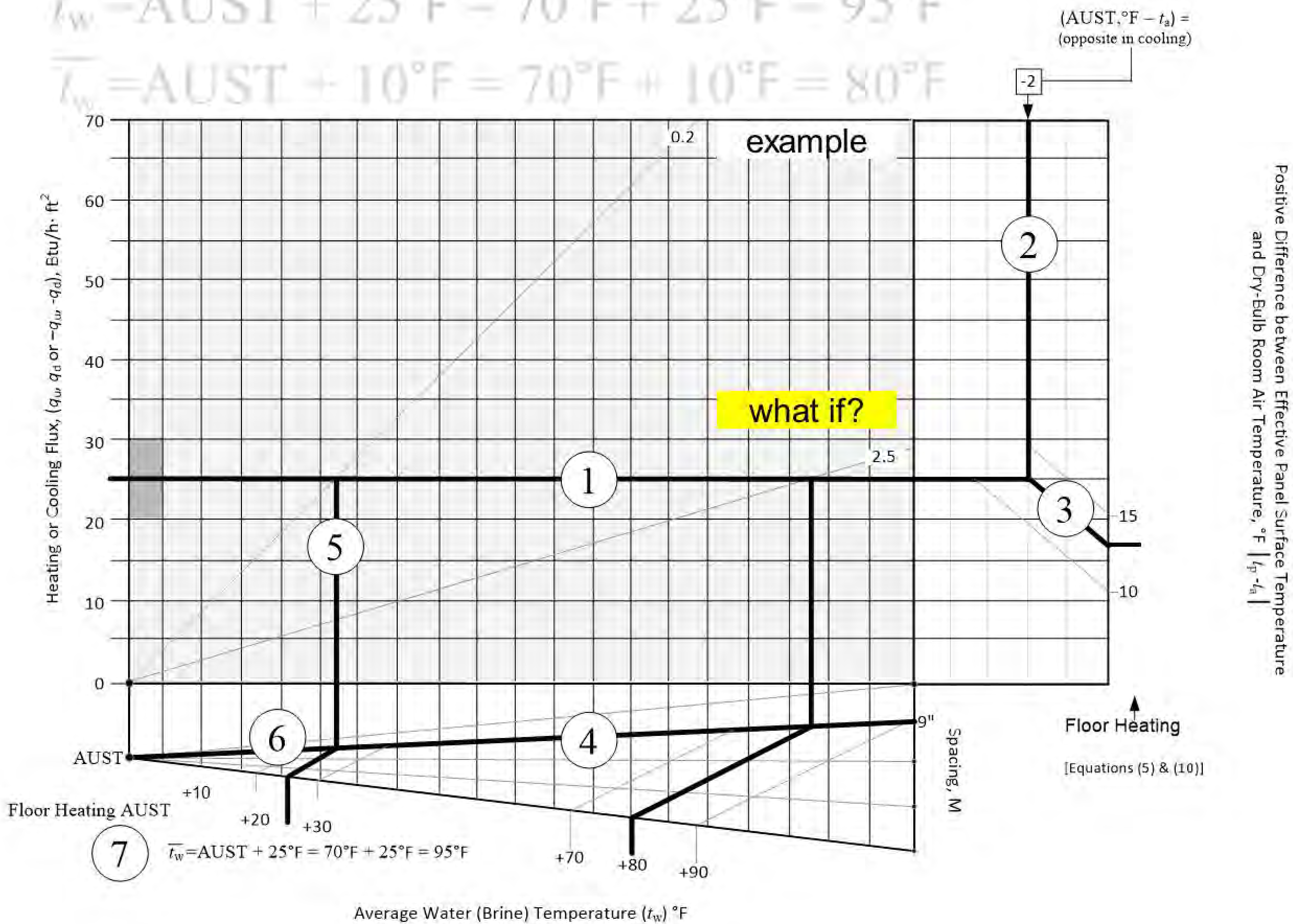
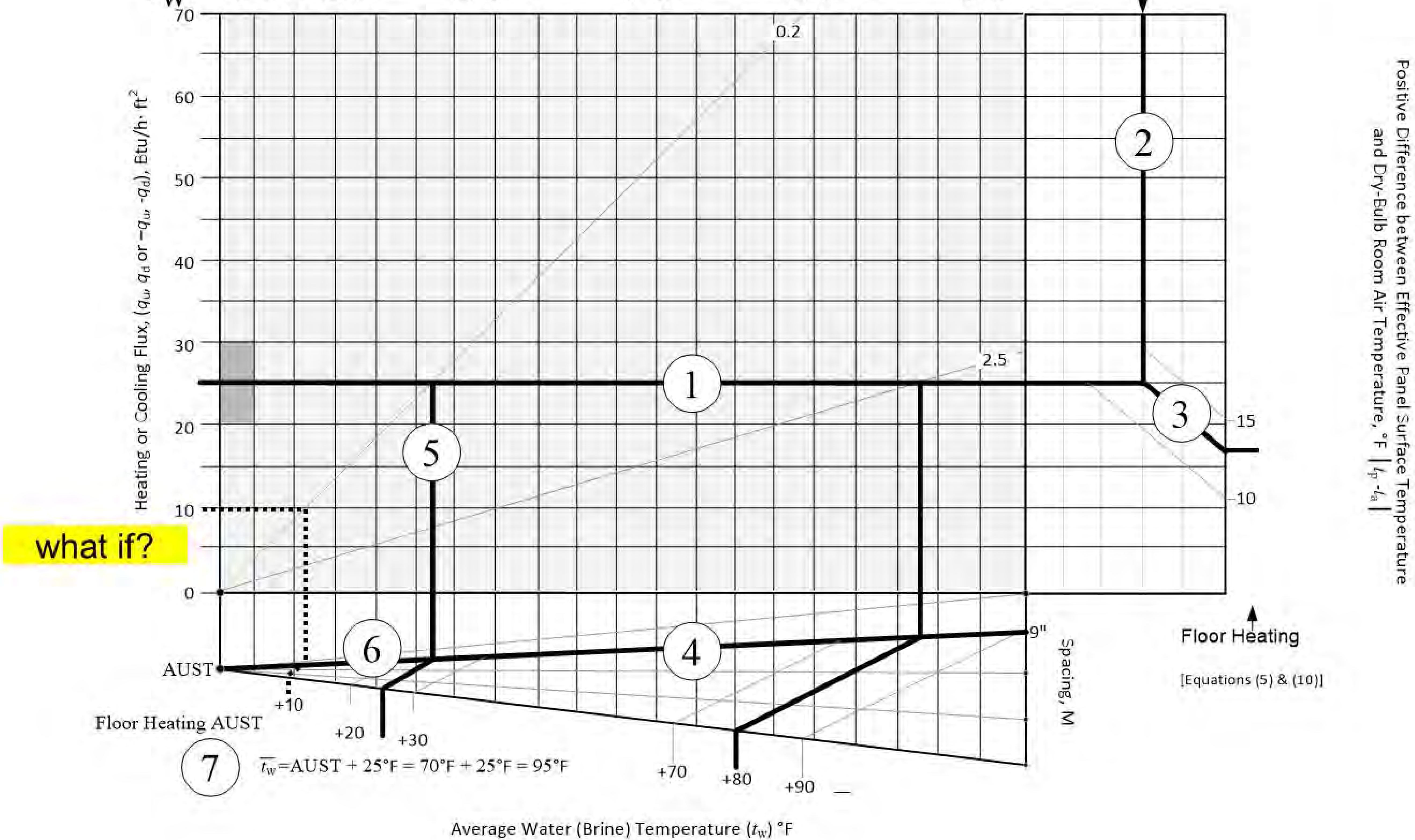


Fig. 9 Design Graph for Heating and Cooling with Floor and Ceiling Panels, Panel Heating and Cooling 6.9, Reprinted With Permission, 2000 ASHRAE Systems and Equipment Handbook, www.ASHRAE.org.

80°F vs 95°F vs 150°F!

$$\overline{t_w} = AUST + 25°F = 70°F + 25°F = 95°F$$

$$\overline{t_w} = AUST + 10°F = 70°F + 10°F = 80°F$$



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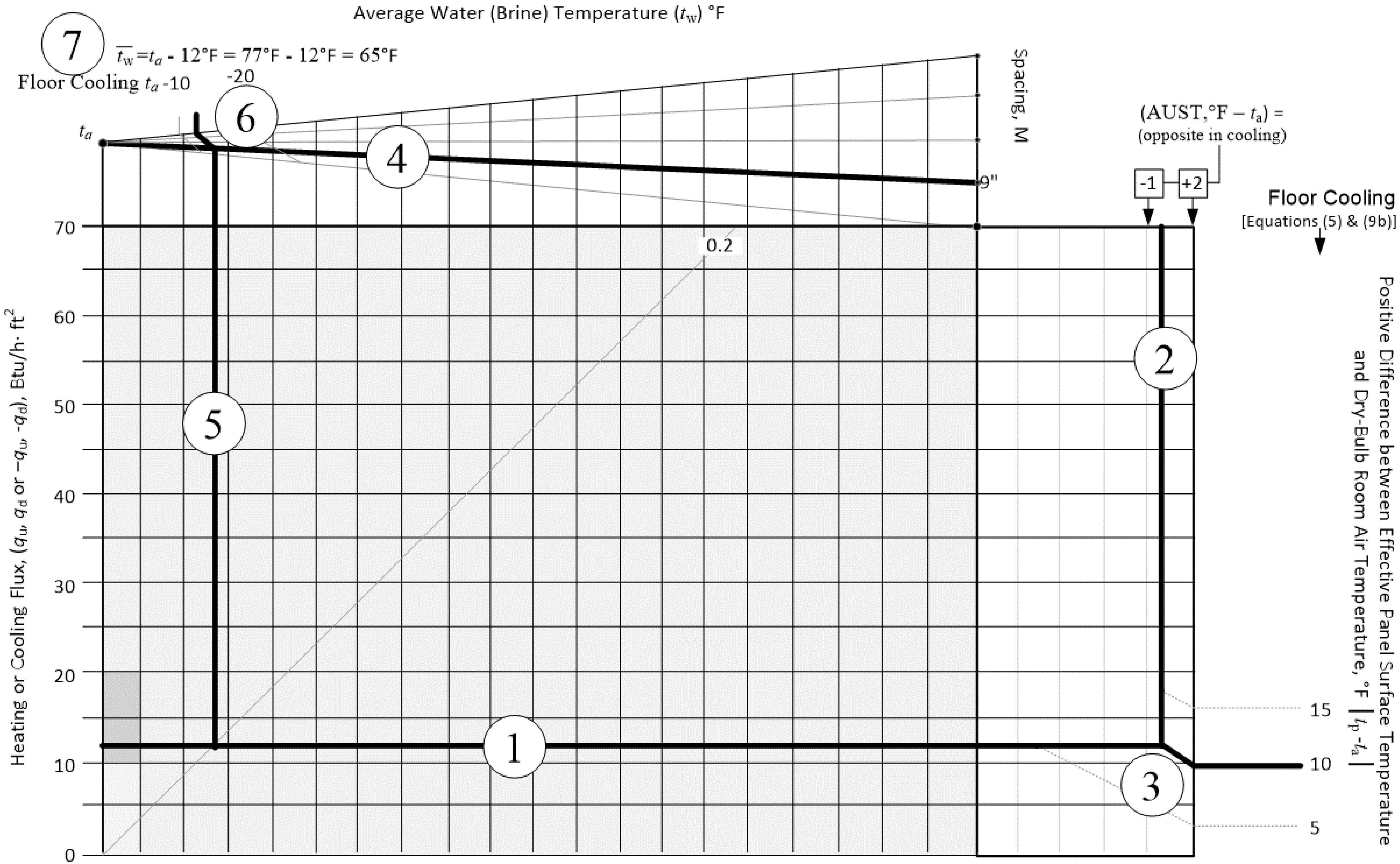


$$\overline{t}_w = t_a - 12°F = 77°F - 12°F = 65°F \text{ (average)}$$

$$t_{w\text{-}s} = \overline{t}_w - (\Box t/2) = 65°F - 8°F/2 = 61°F \text{ (supply)}$$

$$t_{w\text{-}r} = \overline{t}_w + (\Box t/2) = 65°F + 8°F/2 = 69°F \text{ (return)}$$

Fig. 9 Design Graph for Heating and Cooling with Floor and Ceiling Panels, Panel Heating and Cooling 6.9, Reprinted With Permission, 2000 ASHRAE Systems and Equipment Handbook, www.ASHRAE.org.

low temp heating/high temp cooling

is the efficiency enabler

the graph – section 5

energy, exergy, efficiency

entropy, efficacy

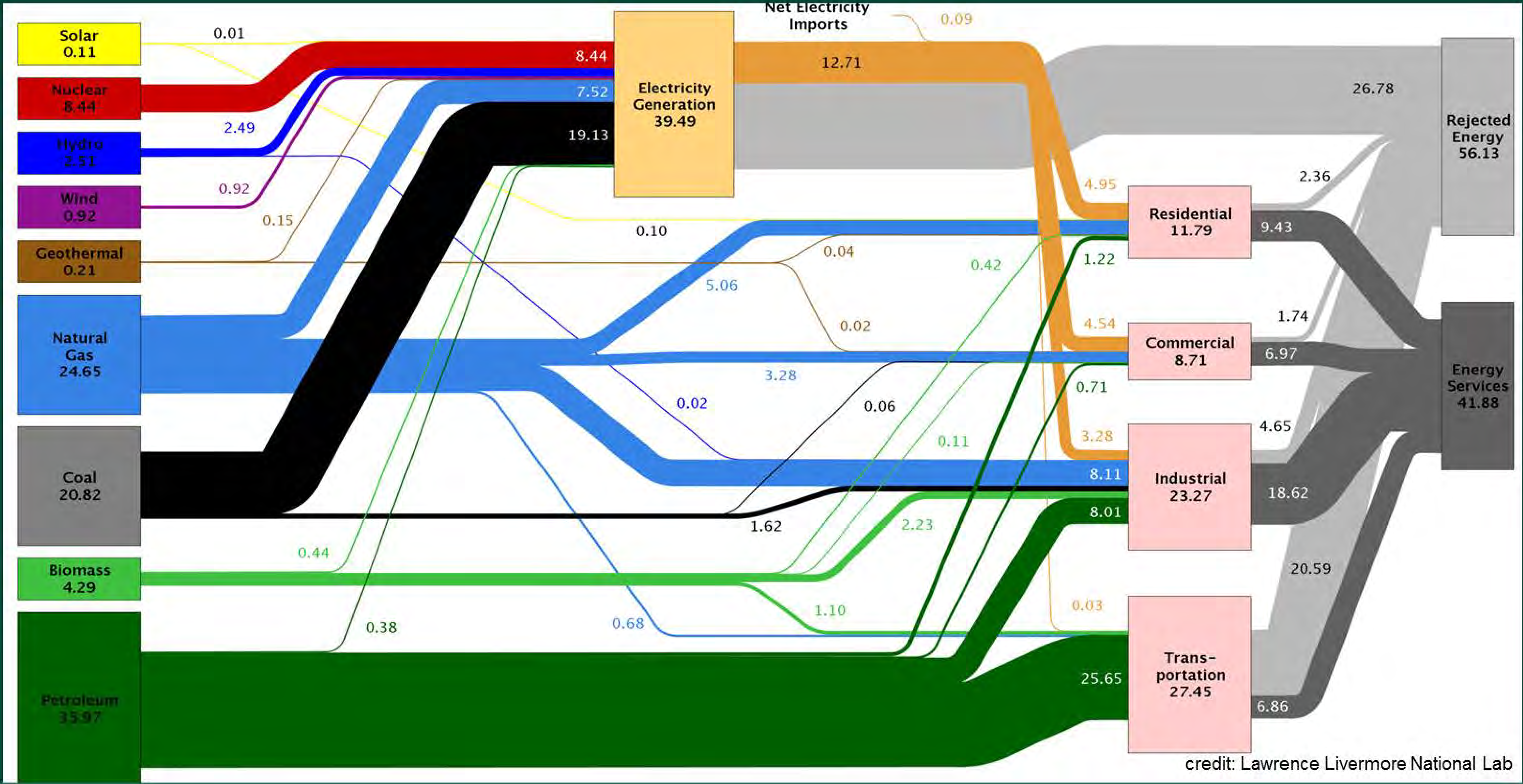
culture: do as we say not as we do

$\frac{0.360 \text{ b}}{7.138 \text{ b}}$

do we really believe the rest of the world should behave as we do?

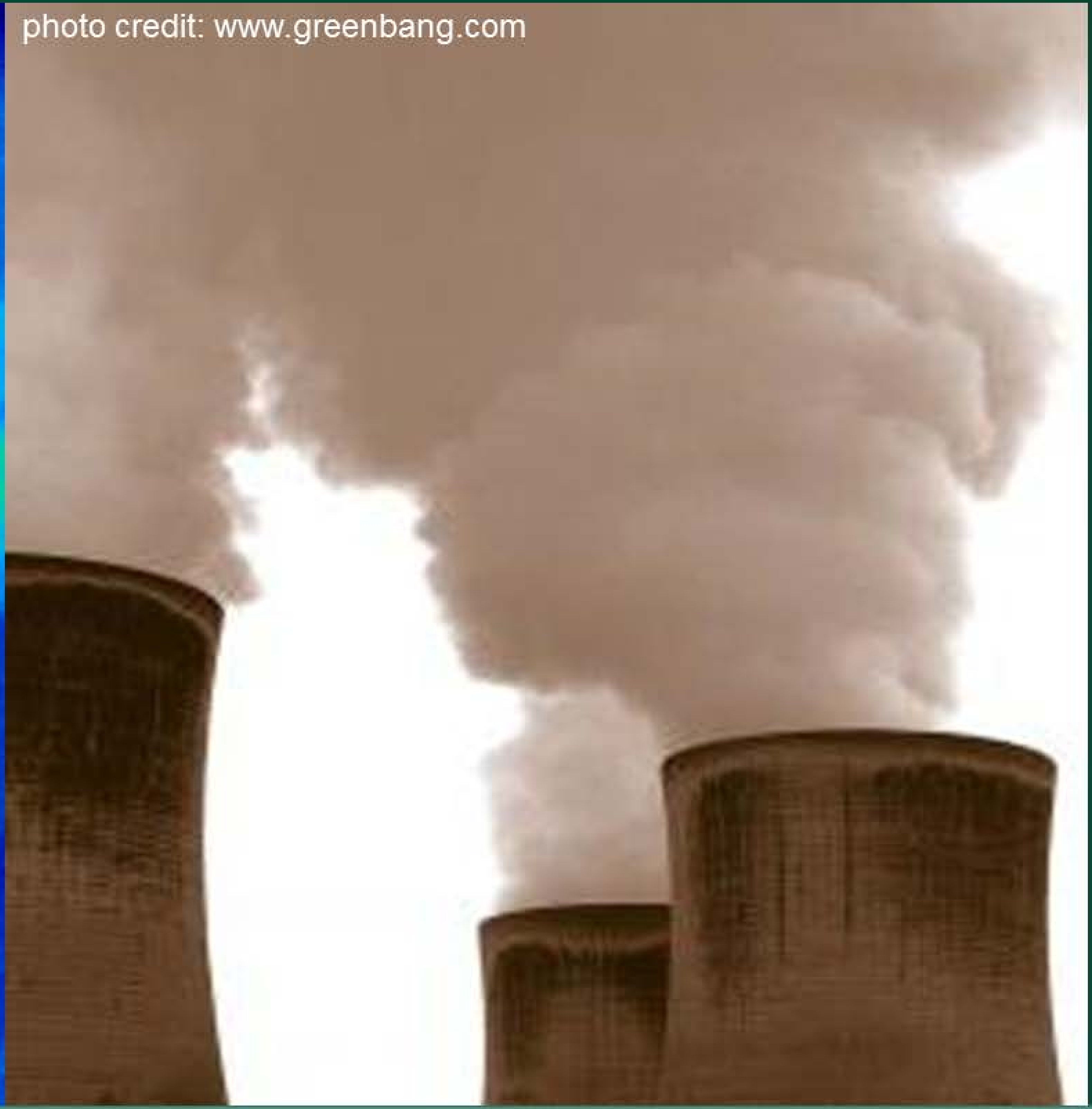
go ahead take a second to think about it

does not describe destruction of quality



credit: Lawrence Livermore National Lab

2nd law exposed



2nd law exposed

photo credit: (c) tony mcconnell / science photo library

photo credit: http://web.mit.edu/renewable-iap09/www/lecture6.html

2nd law exposed

photo credit: (c) tony mcconnell / science photo library

photo figure credit: robert bean

2nd law exposed


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photo credit: http://www.theenergylibrary.com/taxonomy/term/1905

2^{nd} law exposed

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photo credit: (c) uponor

2nd law exposed

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2nd law exposed

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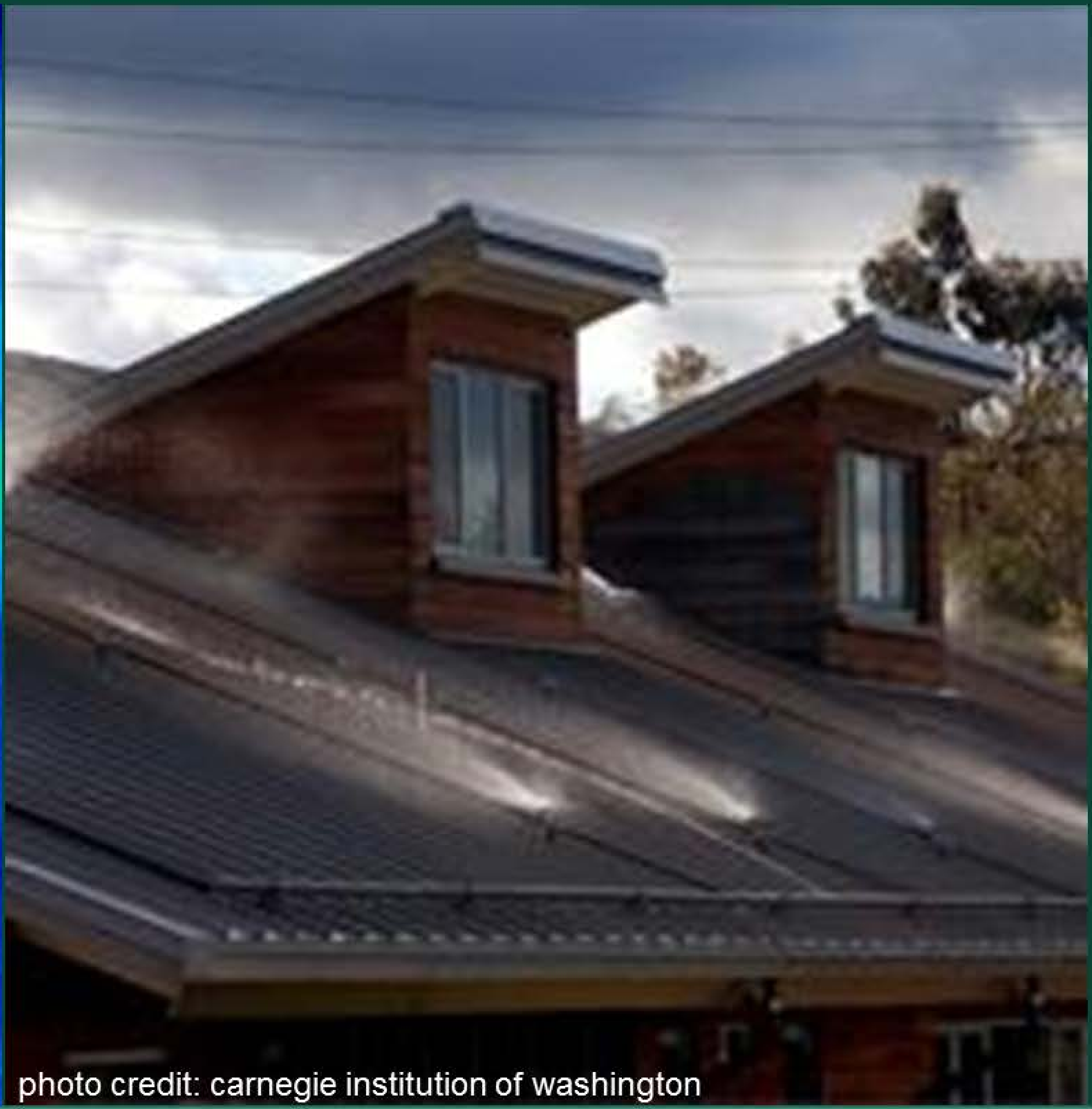
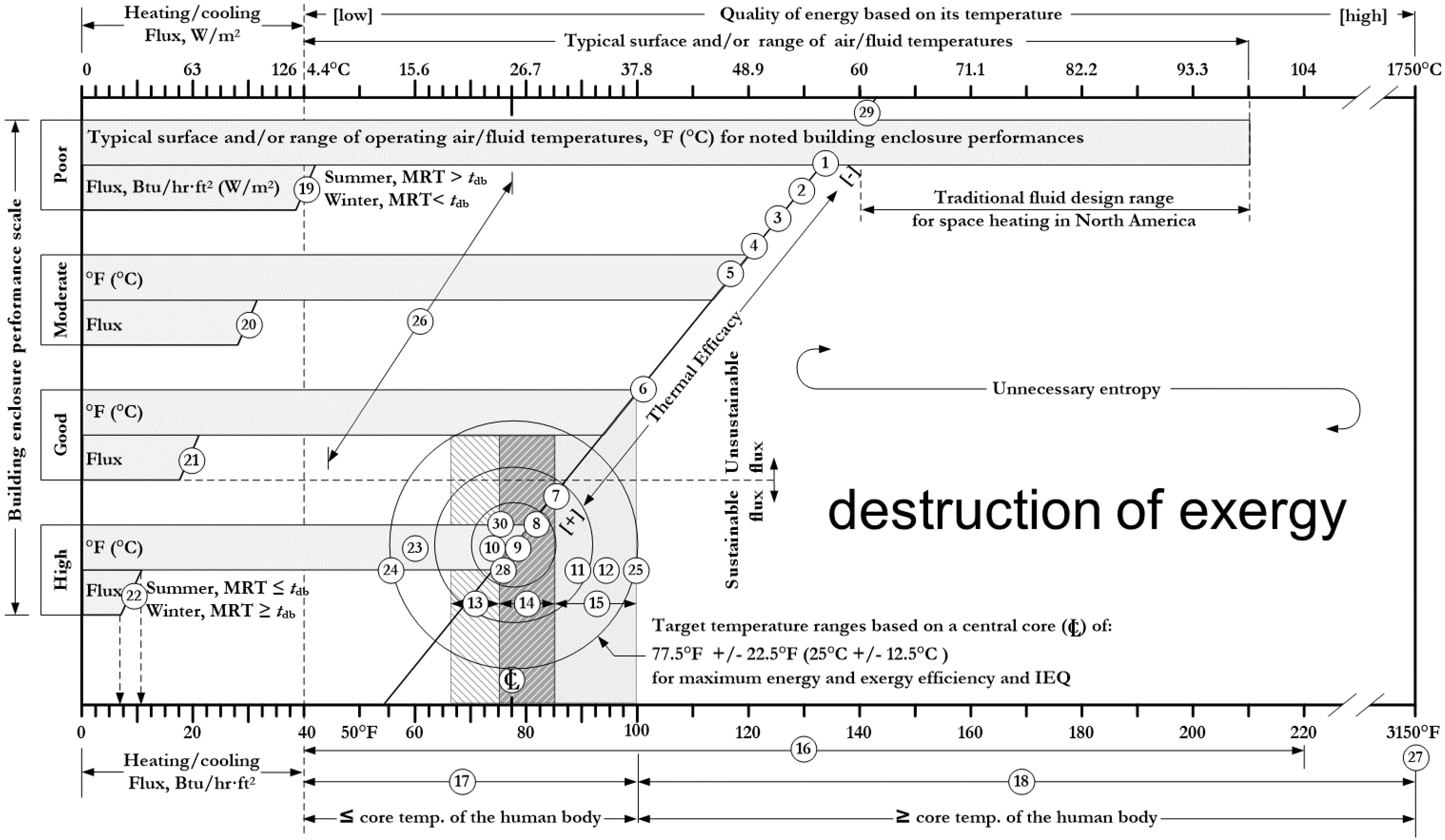


photo credit: carnegie institution of washington

The Interaction & Connection between Buildings, HVAC System & Indoor Environmental Quality



Source: Bean, R. The Interaction and Connection between Buildings, HVAC System, and Indoor Environmental Quality. ASHRAE IAQ2013, Conference Proceedings. Vancouver, October, 2013

sustainability: intuitive except for building energy

risk to society when conservation

is the exclusive goal

sustainability: intuitive except for building energy

image credit: http://www.gandoza.com

sustainability: intuitive except for building energy

sustainability: intuitive except for building energy

image credit: http://www.gandoza.com

sustainability: intuitive except for building energy

image credit: © http://www.creativeplayplus.com/2010/10/08/all-in-a-days-work-firefighter-career-costumes/

image credit: http://commons.wikimedia.org/wiki/File:US_Navy_031018-N-8295E-266_Damage_Controlmen_spray_fire_hose

sustainability: intuitive except for building energy

image credit: http://hamptonroads.com/2012/06/bill-would-allow-tractors-nc-highspeed-roads

sustainability: intuitive except for building energy

image credit: http://www.strangemilitary.com/images/content/106612.JPG

sustainability: intuitive except for building energy

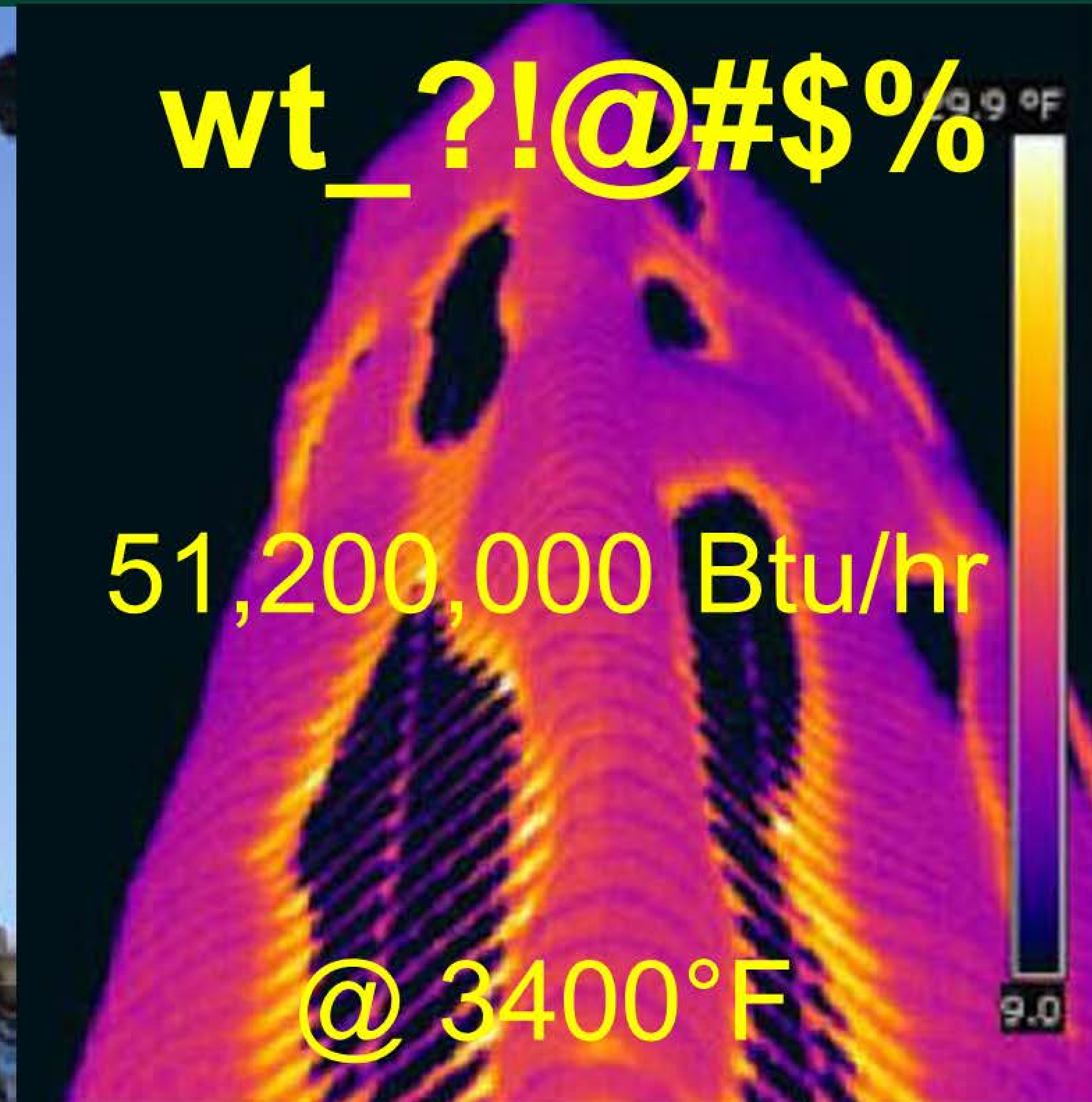
The first building in Chicago to have public charging stations for electric cars.

Chicago's Aqua Tower Captures International Condominium Buyers Along with Design Awards

"ingenious" Pulitzer-Prize winning architectural critic Paul Goldberger of New Yorker magazine

"the most sensuous skyscraper" Chicago Tribune architectural critic Blair Kamin

sustainability: intuitive except for building energy



sustainability: intuitive except for building energy

photo figure credit: unhindered by talent

exergy 101

example 1. exergy (ε), α [1- (T_2 / T_1)], T_2 = reference, T_1 = source	
item	temperature (R)
source: natural gas combustion, T_1 (3400F)	3900
reference: soil, T_2 (40F)	500
exergy value (ε), 1- (T_2 / T_1) = 1-(500/3900) =	**0.872**
considered a high exergy source	

example 2. exergy (ε), α [1- (T_2 / T_1)], T_2 = reference, T_1 = source	
item	temperature (R)
source: wood combustion, T_1 (1500F)	1960
reference: soil, T_2 (40F)	500
exergy value (ε), 1- (T_2 / T_1) = 1-(500/3900) =	**0.745**
considered a higher exergy source	

exergy 101

example 3. exergy (ε), α [1- (T_2 / T_1)], T_2 = reference, T_1 = source	
item	temperature (R)
source: solar thermal, T_1 (220F)	679
reference: soil, T_2 (40F)	500
exergy value (ε), 1- (T_2 / T_1) = 1-(500/510) =	**0.264**
considered a lower exergy source	

example 4. exergy (ε), α [1- (T_2 / T_1)], T_2 = reference, T_1 = source	
item	temperature (R)
source: heat pump – non combustion based, T_1 (100F)	560
reference: soil, T_2 (40F)	500
exergy value (ε), 1- (T_2 / T_1) = 1-(500/510) =	**0.107**
considered a low exergy source when powered by hydro, PV, wind, geothermal, etc	

exergy 101

example 5. exergy (ε), α [1- (T_2 / T_1)], T_2 = reference, T_1 = source	
item	temperature (R)
source: room temperature, T_1 (68F)	528
reference: soil, T_2 (40F)	500
exergy value (ε), 1- (T_2 / T_1) = 1-(500/528) =	**0.053**
considered a low exergy source/load	

exergy 101

example 1. exergy (ε), α [1- (T_2 / T_1)], T_2 = reference, T_1 = source	
item	temperature (R)
source: room temperature, T_1 (68F)	528
reference: soil, T_2 (40F)	500
exergy value (ε), 1- (T_2 / T_1) = 1-(500/528) =	**0.053**
considered a low exergy source/load	

exergy efficiency (ε%), = $\varepsilon_{load}/\varepsilon_{source}$ using natural gas to heat a space	
Item	exergy
exergy of source (ε_s), natural gas combustion, T_1 (3400F)	0.872
exergy of load at room temperate T_2 (68F)	0.053
exergy efficiency (ε%), = $\varepsilon_{required}/\varepsilon_{source}$ = 0.053/0.872	**6.1%**
without cascading loads = poor match	

exergy 101

example 2. exergy (ε), α [1- (T_2 / T_1)], T_2 = reference, T_1 = source	
item	temperature (R)
source: room temperature, T_1 (68F)	528
reference: soil, T_2 (40F)	500
exergy value (ε), 1- (T_2 / T_1) = 1-(500/528) =	0.053
considered a low exergy source	

exergy efficiency (ε%), = $\varepsilon_{load}/\varepsilon_{source}$ using wood to heat a space	
item	exergy
exergy of source (ε_s), wood combustion, T_1 (1500F)	0.745
exergy of load at room temperate T_2 (68F)	0.053
exergy efficiency (ε%), = $\varepsilon_{required}/\varepsilon_{source}$ = 0.053/0.107 =	**7.1%**
without cascading loads = poor match	

exergy 101

example 3. exergy (ε), α [1- (T_2 / T_1)], T_2 = reference, T_1 = source	
item	temperature (R)
source: room temperature, T_1 (68F)	528
reference: soil, T_2 (40F)	500
exergy value (ε), 1- (T_2 / T_1) = 1-(500/528) =	0.053
considered a low exergy source	

exergy efficiency (ε%), = $\varepsilon_{load}/\varepsilon_{source}$ using solar thermal to heat a space	
item	exergy
exergy of source (ε_s), solar thermal, T_1 (220F)	0.264
exergy of load at room temperate T_2 (68F)	0.053
exergy efficiency (ε%), = $\varepsilon_{required}/\varepsilon_{source}$ = 0.053/0.264 =	**20.1%**
a better match, but could be improved with cascading loads such as dhw, pools, mua	

exergy 101

example 4. exergy (ε), α [1- (T_2 / T_1)], T_2 = reference, T_1 = source	
item	temperature (R)
source: room temperature, T_1 (68F)	528
reference: soil, T_2 (40F)	500
exergy value (ε), 1- (T_2 / T_1) = 1-(500/528) =	0.053
considered a low exergy source	

exergy efficiency (ε%), = $\varepsilon_{load}/\varepsilon_{source}$ using heat pump* to heat a space	
item	exergy
exergy of source (ε_s), heat pump, T_1 (100F)	0.107
exergy of load at room temperate T_2 (68F)	0.053
exergy efficiency (ε%), = $\varepsilon_{required}/\varepsilon_{source}$ = 0.053/0.107 =	**49.5%**
*great match if electricity is hydro, wind, pv, geothermal etc but not combustion!	

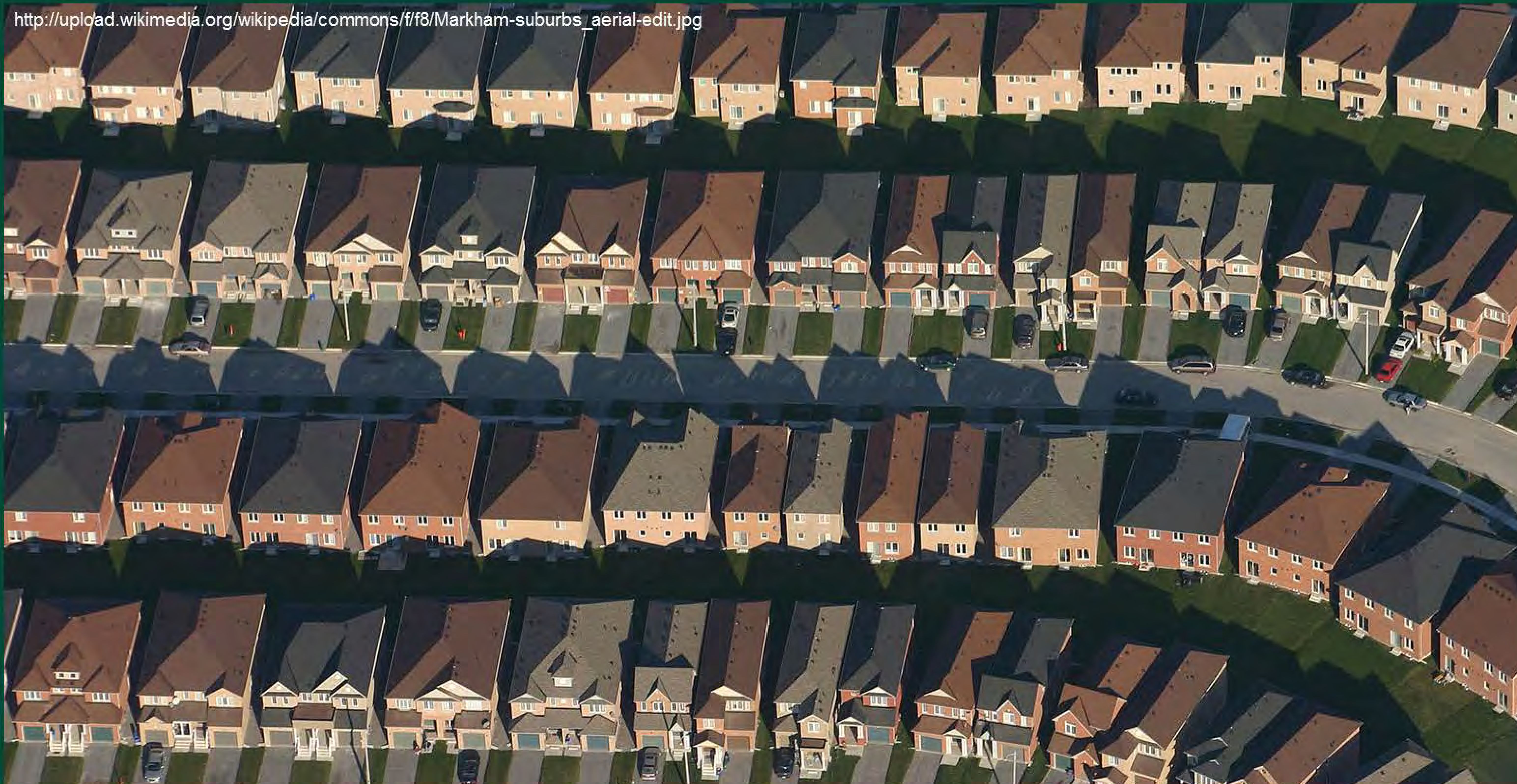
paradox of the 21st century

if combustion is involved…

the more efficient the building the

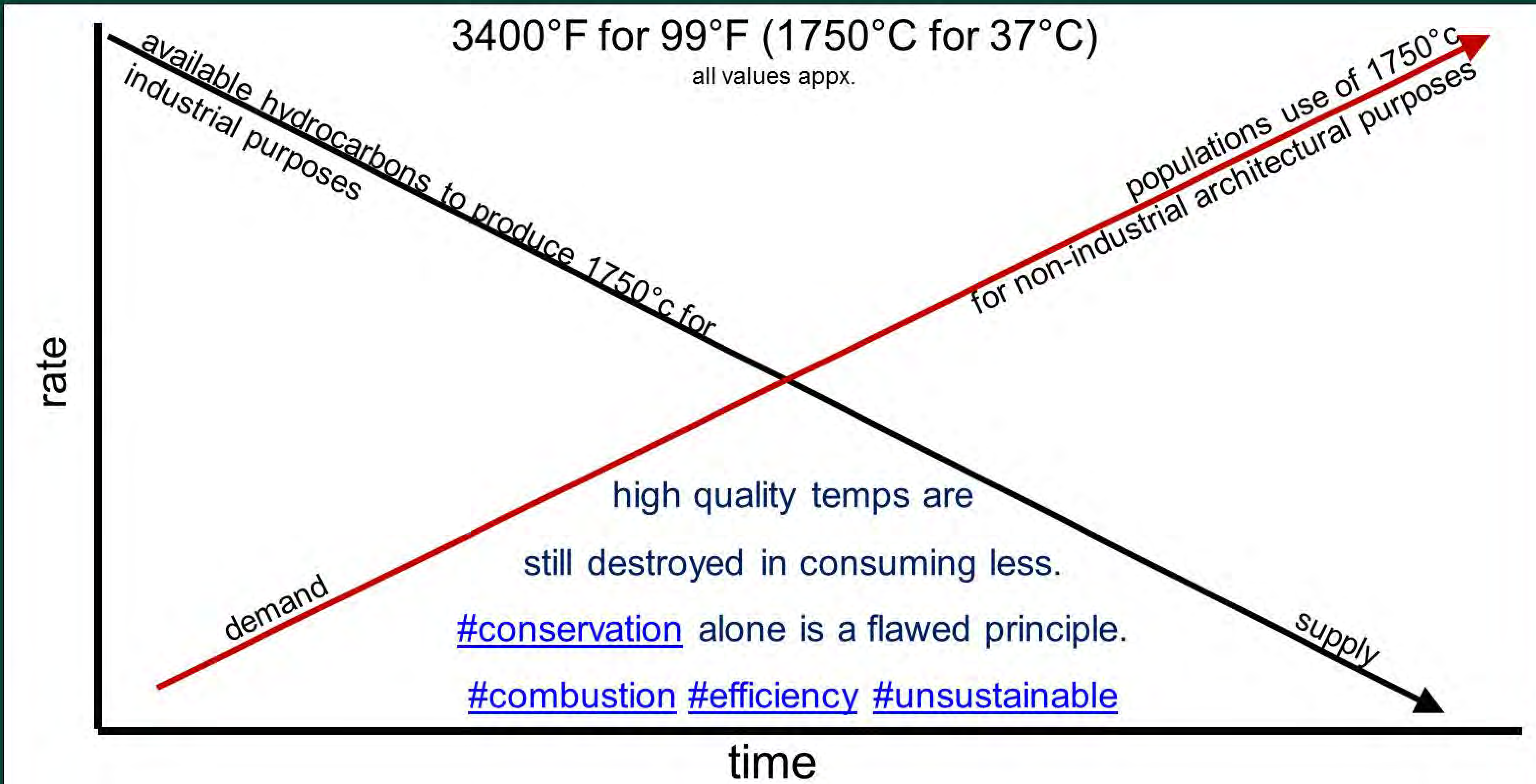
less exergy efficient the system

paradox of the 21st century

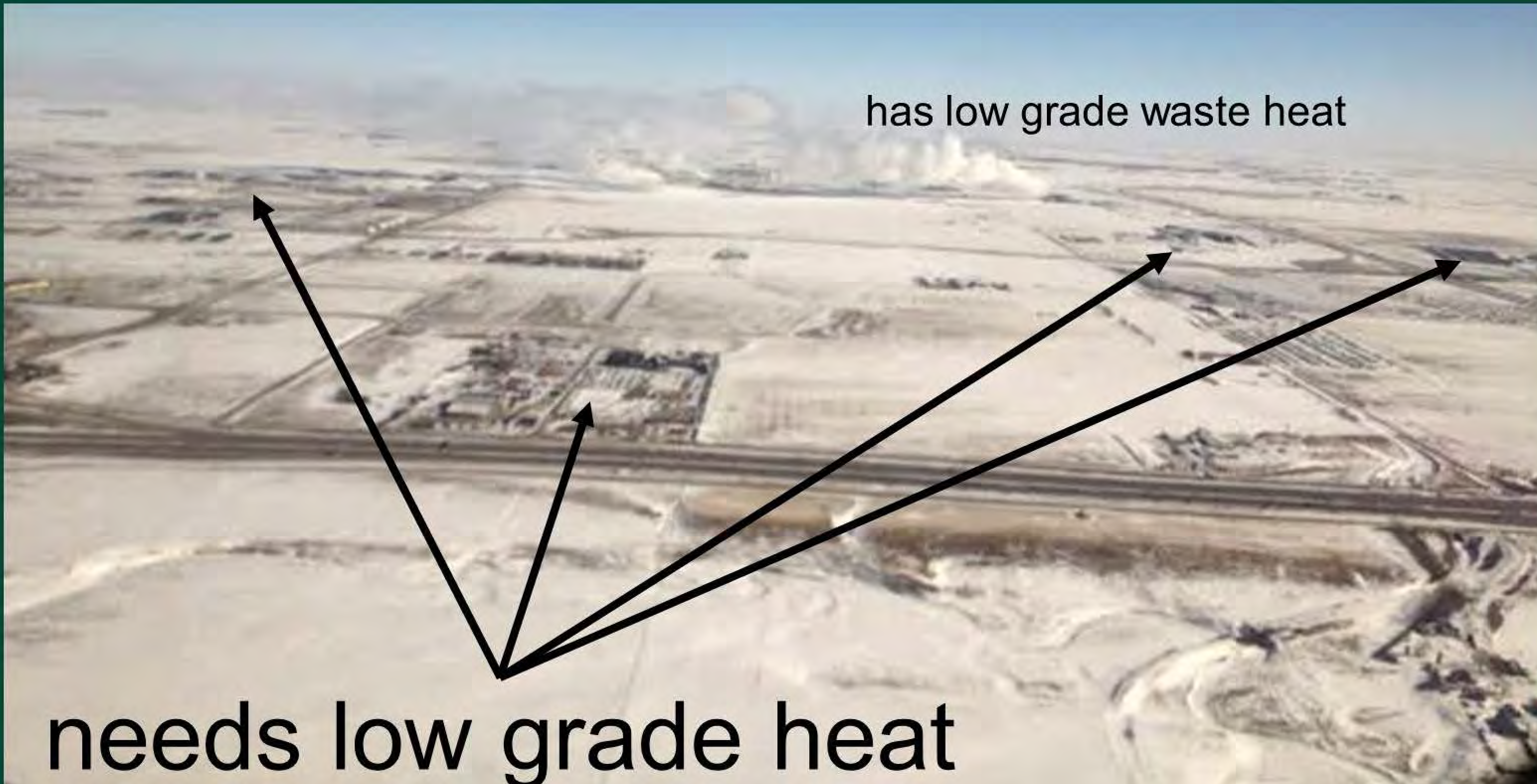


paradox of the 21st century

paradox of the 21st century



you don’t need an engineering degree to figure it out



setback thermostats & combustion

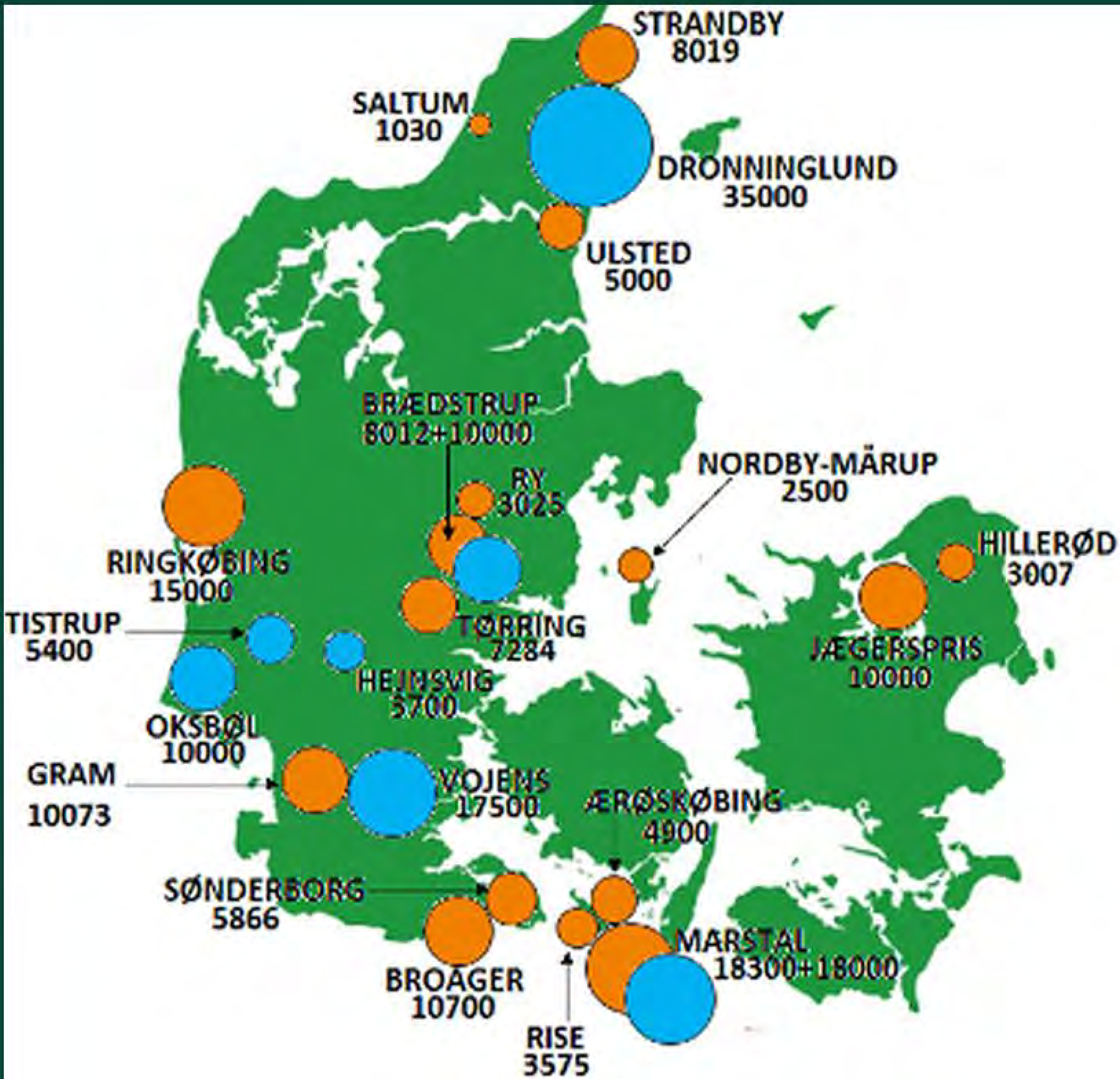
promoting 2,4,6°F setback

while ignoring the destruction

of 3300°F …

feel free to complete the thought on your own

lowEx examples



Denmark's large scale solar district heating plants in m^2

$1m^2 = 10.76ft^2$

Operating

Planned

lowEx examples

lowEx examples

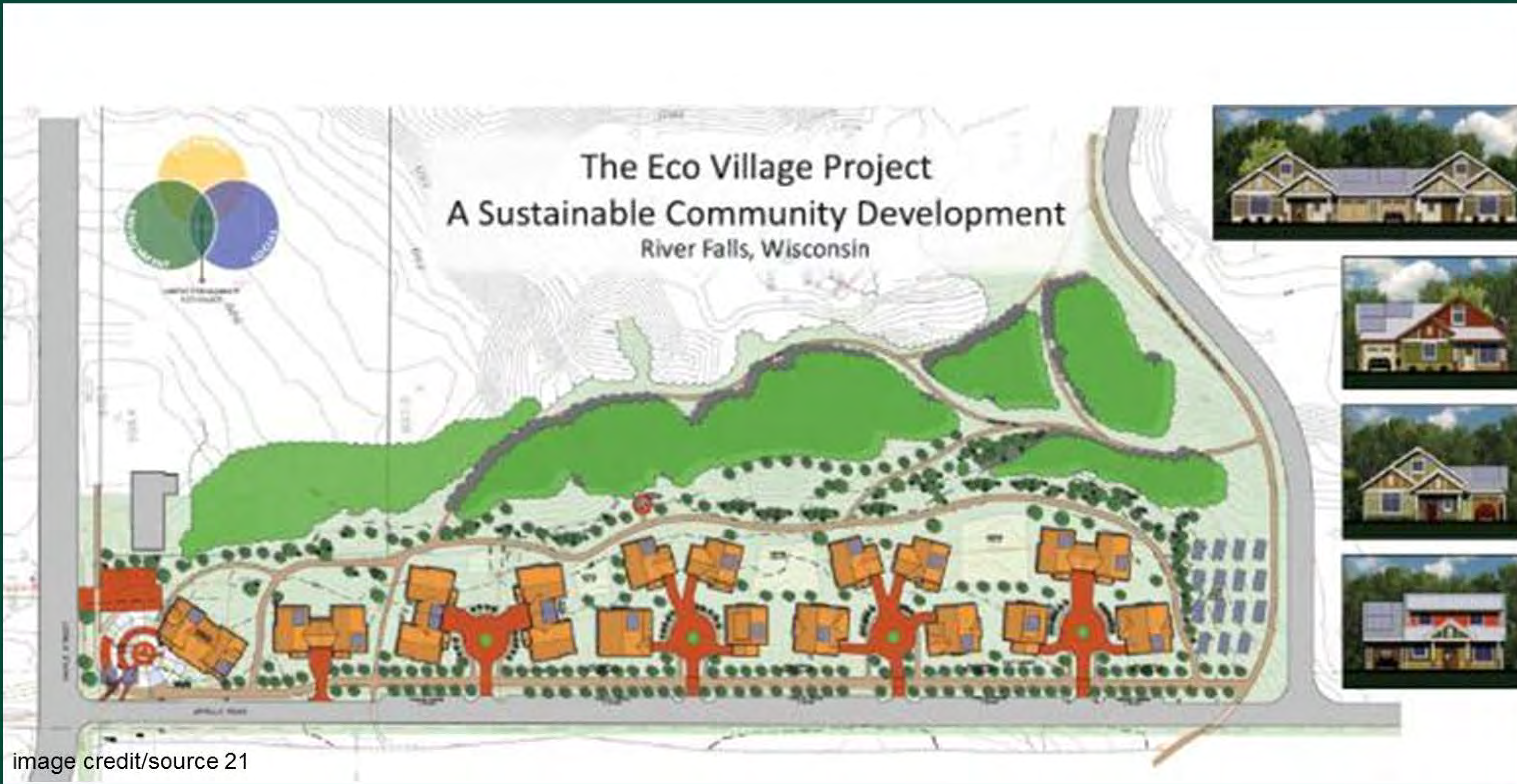
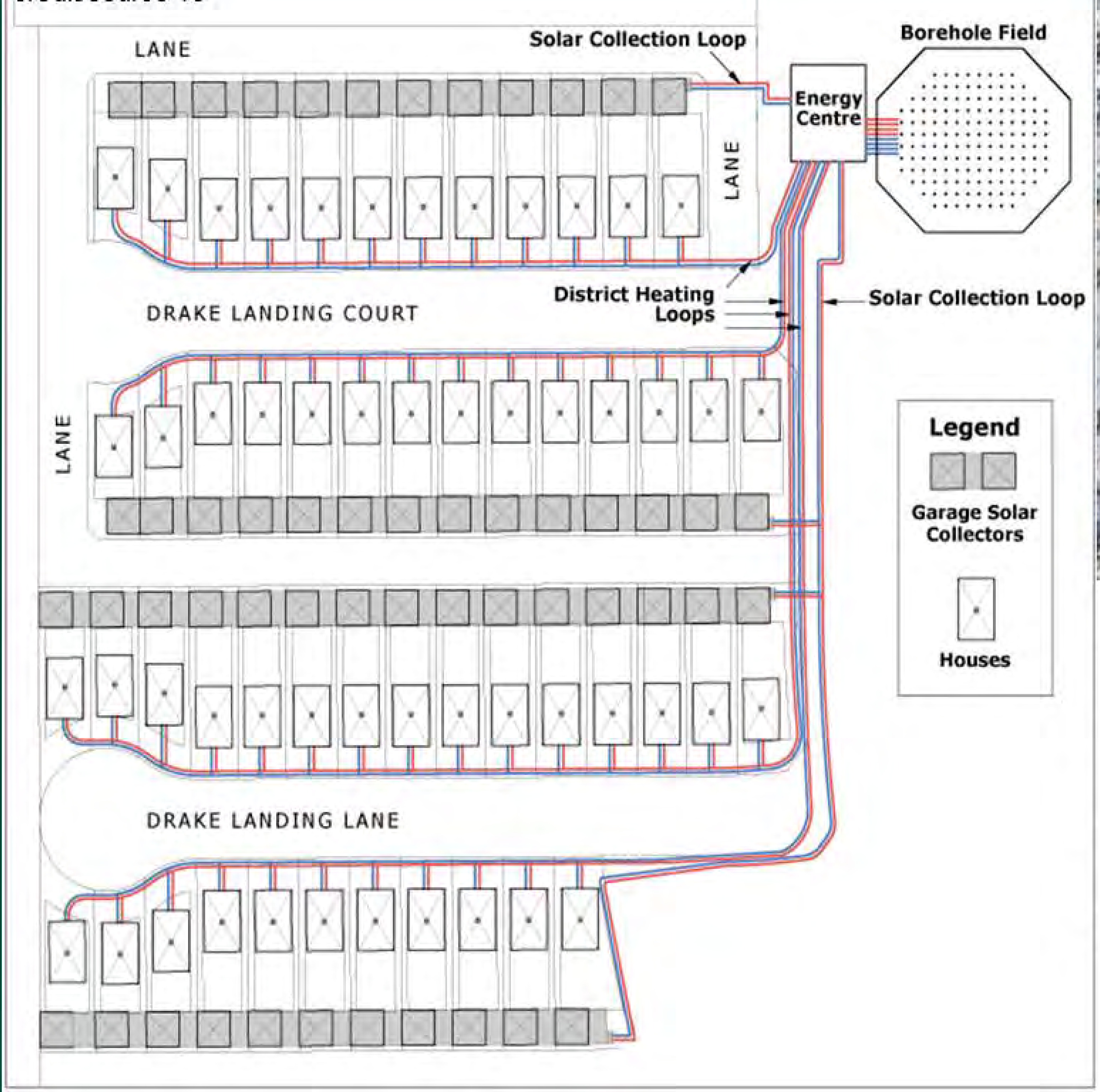


image credit/source 21

lowEx examples

credit/source 19



Drake Landing, Alberta, Canada

R-2000 single family homes, 90% of residential space heating needs will be met by solar thermal energy.

IEA lowEx projects

International Energy Agency's Energy in Buildings and Communities Programme

ONGOING PROJECTS
COMPLETED PROJECTS

EBC Annex 37 Low Exergy Systems for Heating and Cooling

ONGOING PROJECTS
COMPLETED PROJECTS

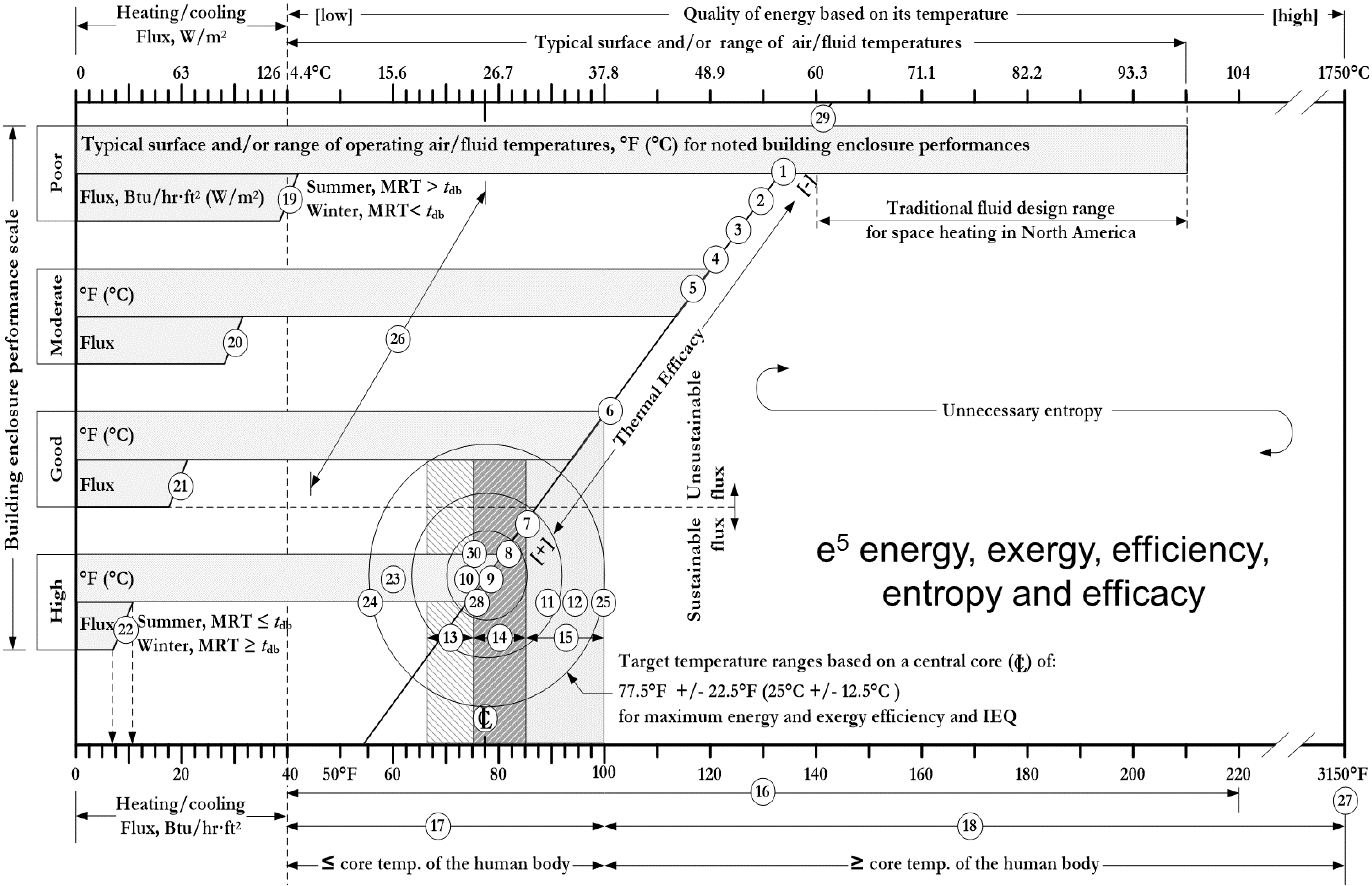
EBC Annex 49 Low Exergy Systems for High Performance Buildings and Communities

ONGOING PROJECTS
COMPLETED PROJECTS

EBC Annex 59 High Temperature Cooling and Low Temperature Heating in Buildings

ONGOING PROJECTS
COMPLETED PROJECTS

EBC Annex 64 LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles


Heating/cooling Flux, W/m²
[low]
Quality of energy based on its temperature
[high]
Typical surface and/or range of air/fluid temperatures
0
63
126
4.4°C
15.6
26.7
37.8
48.9
60
71.1
82.2
93.3
104
1750°C
Building enclosure performance scale
Poor
Moderate
Good
High
Typical surface and/or range of operating air/fluid temperatures, °F (°C) for noted building enclosure performances
Flux, Btu/hr·ft² (W/m²)
Summer, MRT > t_{db}
Winter, MRT< t_{db}
Traditional fluid design range
for space heating in North America
°F (°C)
Flux
Thermal Efficacy
Unnecessary entropy
Unsustainable flux
Sustainable flux
[-]
[+]
Summer, MRT ≤ t_{db}
Winter, MRT ≥ t_{db}
e⁵ energy, exergy, efficiency,
entropy and efficacy
Target temperature ranges based on a central core (℄) of:
77.5°F +/- 22.5°F (25°C +/- 12.5°C)
for maximum energy and exergy efficiency and IEQ
0
20
40
50°F
60
80
100
120
140
160
180
200
220
3150°F
Heating/cooling Flux, Btu/hr·ft²
≤ core temp. of the human body
≥ core temp. of the human body

ASHRAE

serve humanity

and

promote a sustainable world

…only if we focus on 2nd law

at the end of the day…

energy • entropy • efficiency

• efficacy • exergy

+

green principles

=

sustainability

at the end of the day…