Comprehensive Certificate Course for
BEAM Plus on Health and Wellbeing
23 July 2026 (Thu)

Thermal Comfort Design

Ir Dr. Sam C. M. Hui
Adjunct Assistant Professor
Department of Mechanical Engineering
The University of Hong Kong
E-mail: cmhui@hku.hk

Jun 2026

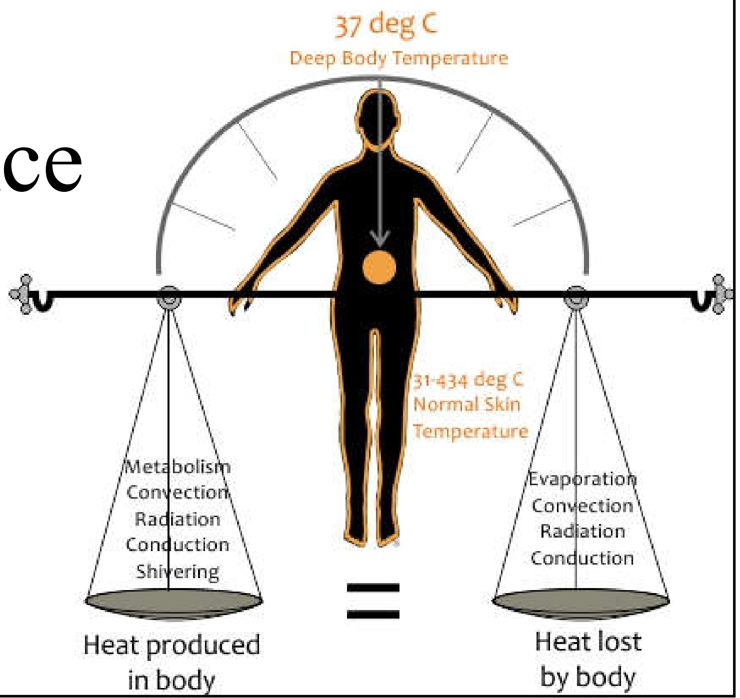
About the Lecturer

- ***Ir Dr. Sam C. M. Hui*** *許俊民 博士 工程師* http://ibse.hk/cmhui
  - Adjunct Assistant Professor 客席助理教授, HKU Dept of Mech Engg
  - PhD, BEng(Hons), CEng, CEM, BEMP, HBDP, MASHRAE, MCIBSE, MHKIE, MIESNA, LifeMAEE, AssocAIA
    - CEng = Chartered Engineer
    - CEM = Certified Energy Manager
    - BEMP = Building Energy Modeling Professional
    - HBDP = High-performance Building Design Professional
    - LifeMAEE = Life Member, Association of Energy Engineers
    - AssocAIA = Associate Member, American Institute of Architects
  - ASHRAE Distinguished Lecturer (2009-2011)
  - President, ASHRAE Hong Kong Chapter (2006-2007)

About ASHRAE

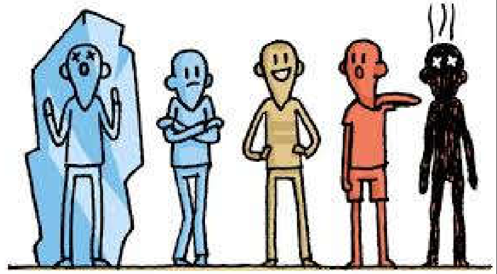
- ASHRAE = American Society of Heating,
- Refrigerating and Air-Conditioning Engineers
  - Global leader in the arts and sciences of heating, ventilation, air conditioning and refrigeration
  - www.ashrae.org
  - Important ASHRAE Standards:
    - 55: thermal comfort
    - 62.1: indoor air quality
    - 90.1: building energy conservation
    - 135: BACnet (building automation & control)
    - 189.1: high performance green buildings

Contents



37 deg C
Deep Body Temperature
31-434 deg C
Normal Skin
Temperature
Metabolism
Convection
Radiation
Conduction
Shivering
Heat produced
in body
=
Evaporation
Convection
Radiation
Conduction
Heat lost
by body

1. Introduction



- What is Thermal Comfort? (Definition)

熱舒適

  - "That condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation."
  - Feel neither too hot nor too cold
    - With a balanced exchange of heat between the body and its environment
- ANSI/ASHRAE Standard 55-2023, Section 3
  - A lack of noticing discomfort
  - Ability to focus on the work at hand

What is Thermal Comfort?

Definition

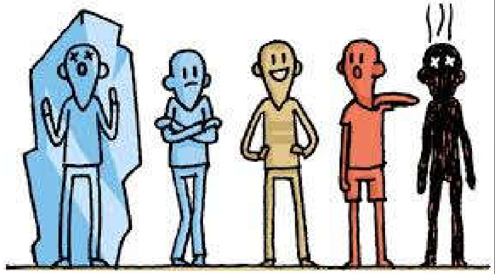
- That condition of mind which expresses satisfaction with the thermal environment.

ISO 7730

Thermal Environments

Thermal Comfort is a matter of many parameters - **Not** only the air temperature.

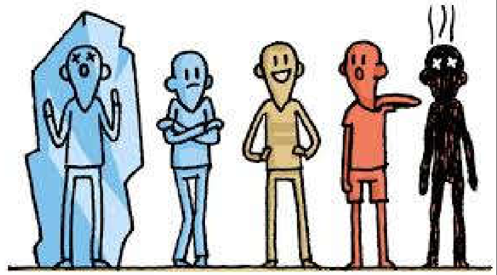
1. Introduction



- Thermal comfort is experienced via a number of conscious interactions between three personal and environment factors
  - Physiological: the way our bodies work and interact with our environment
  - Physical: the main parameters of the environment around us (air temperature, air humidity, air movement, room surface temperature)
  - Socio Psychological: the way we feel as a whole (for example, if we are tired, stressed, happy…) and the kind of social environment we live in

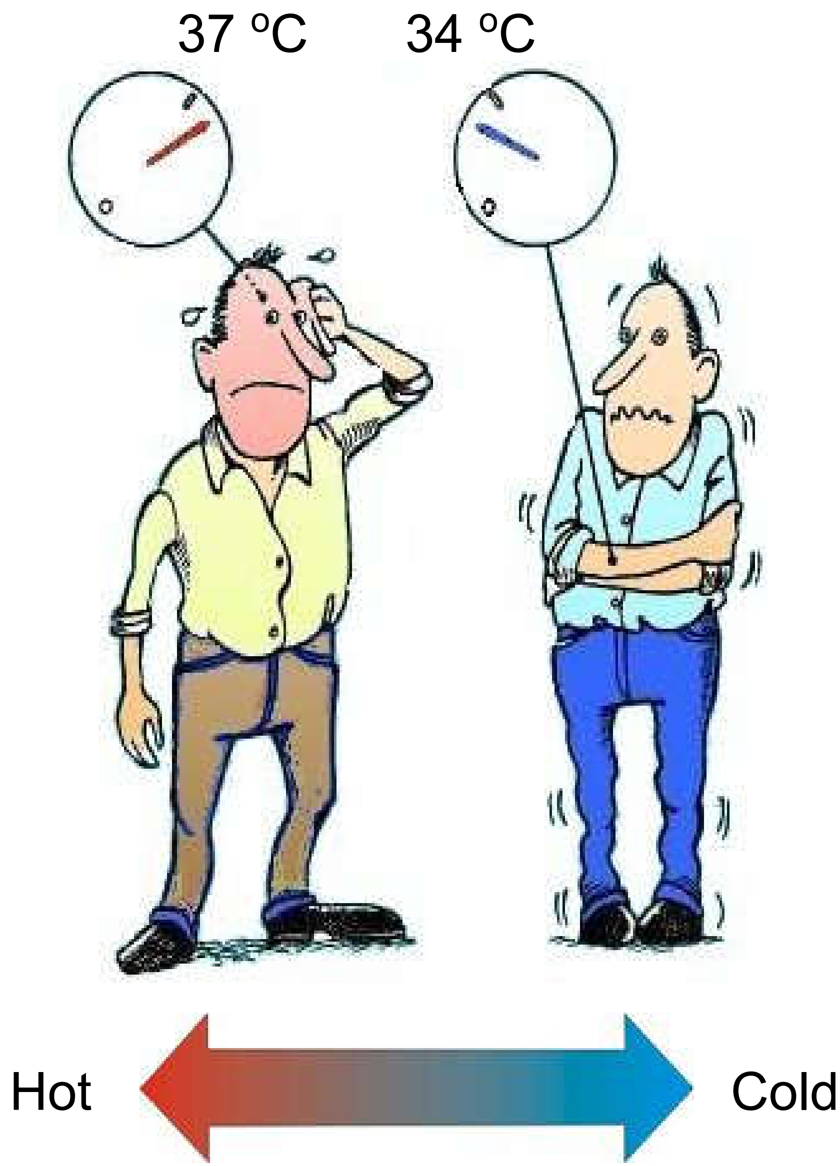
(See also: Thermal Comfort (Saint-Gobain) https://multicomfort.saint-gobain.com/comforts-and-solutions/thermal-comfort)

1. Introduction

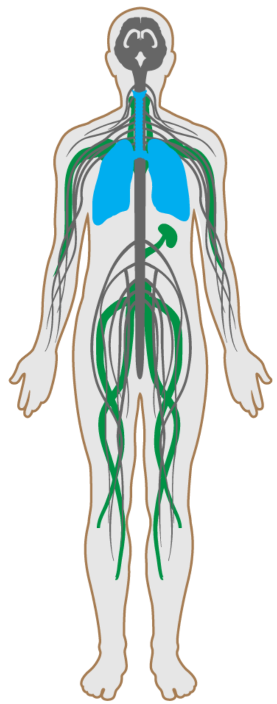


- Other factors affecting thermal comfort:
  - Age
    - Sensation of old people and younger people
  - Adaptation
    - People in warm climates may adapt to hot environment
  - Sex
    - Women: lower skin temperature, evap. loss & lower metablic rate
    - Clothing and perferrence of temperature

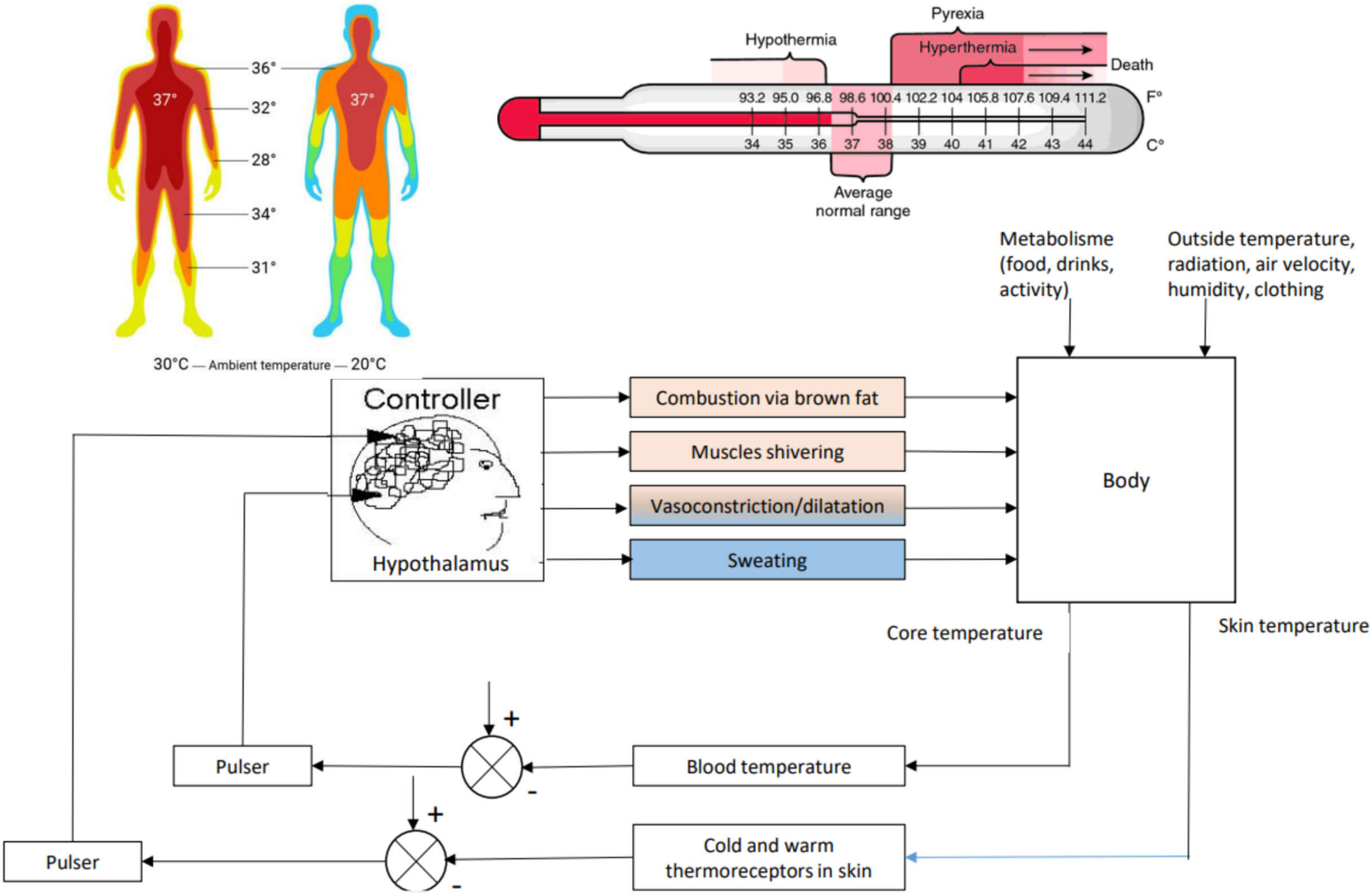
Body Temperature



- Normal body core temperature: 37 °C.
- We have separate Heat- and Cold-sensors.
  - Heat sensor is located in hypothalamus. Signals when temperature is higher than 37 °C.
  - Cold sensors are located in the skin. Send signals when skin temperature is below 34 °C.
- Heating mechanism:
  - Reduced blood flow.
  - Shivering.
- Cooling mechanism:
  - Increased blood flow.
  - Sweating (Evaporation).

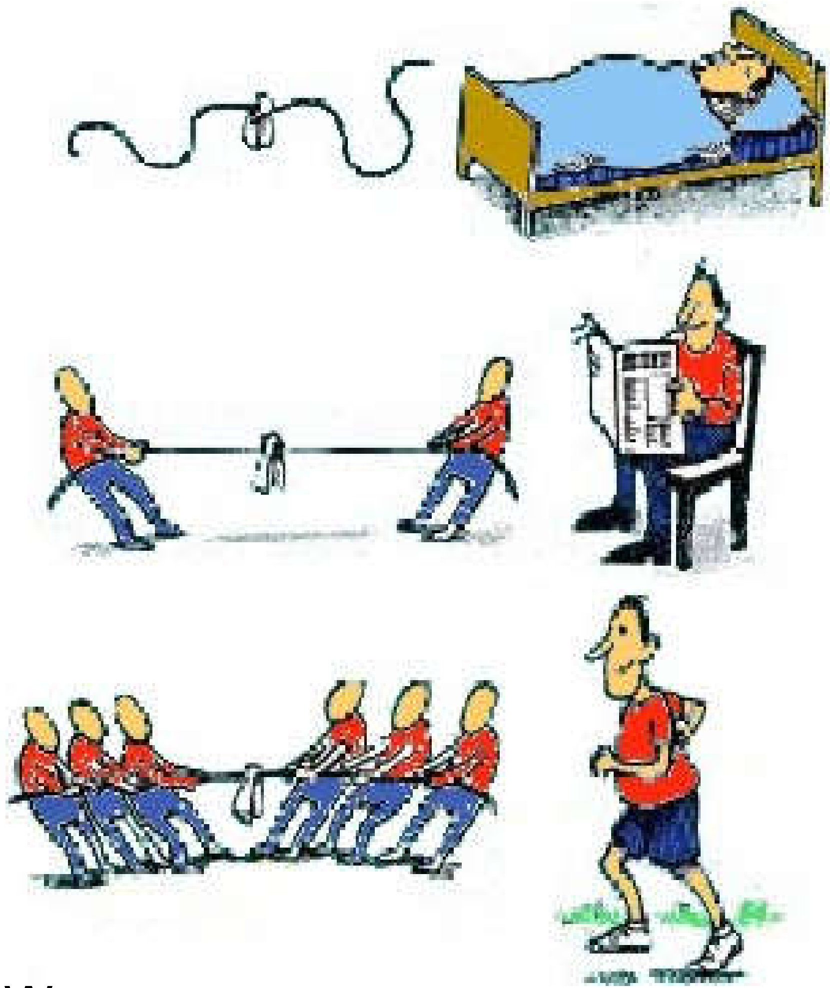


Block diagram of the body temperature control (thermoregulation)



(Source: https://ocw.tudelft.nl/wp-content/uploads/Thermal_Comfort_Reader__Comfort_and_Health_in_Buildings.pdf)

Perception of Thermal Environment



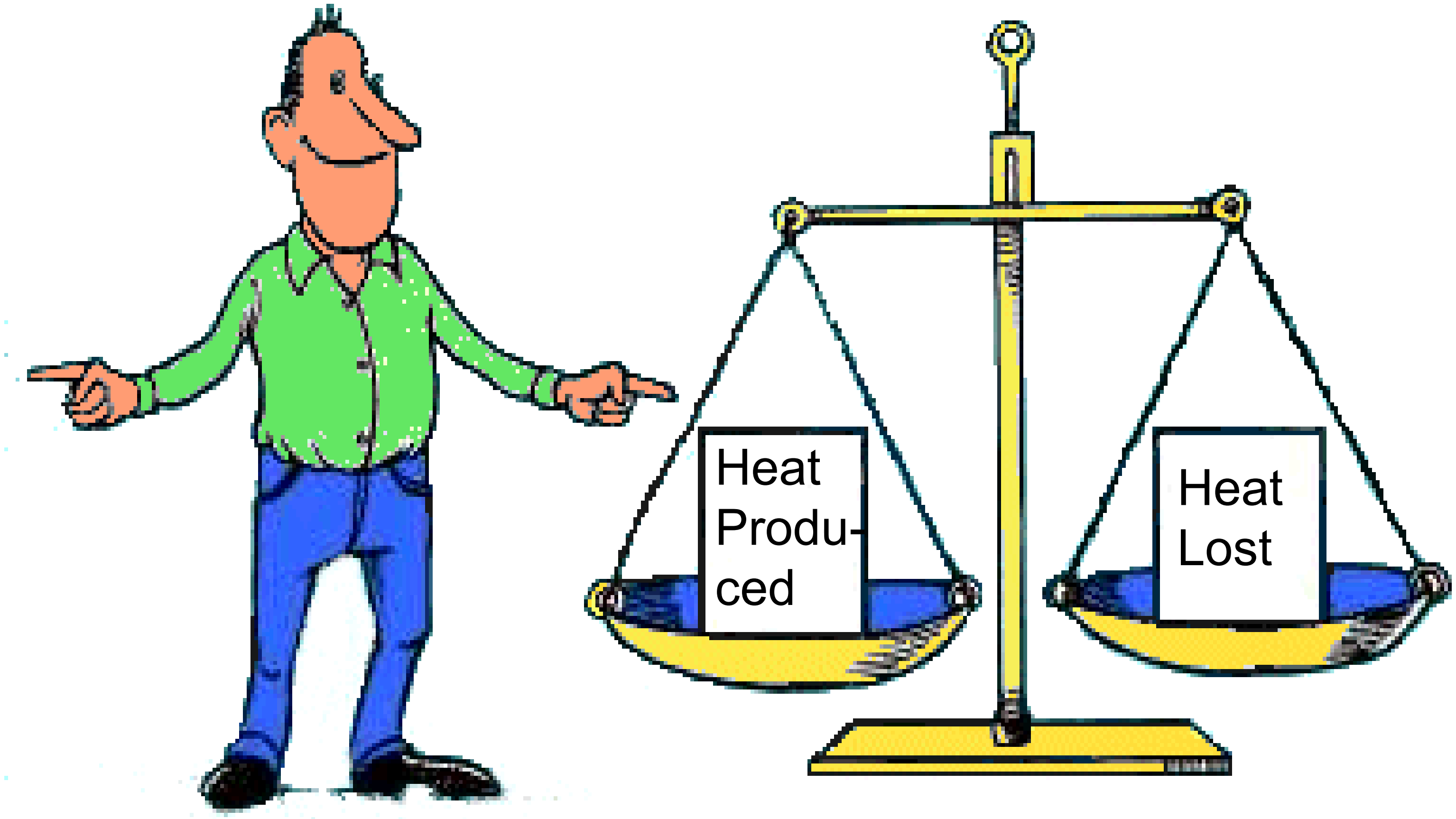
Warm impulses

Cold impulses

Activity

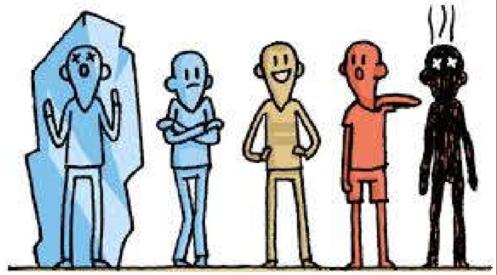
- Heat sensor in hypothalamus send impulses when temperature exceeds 37 ºC.
- Cold sensors sends impulses when skin temperature below 34 ºC.
- The bigger temperature difference, the more impulses.
- If impulses are of same magnitude, you feel thermally neutral.
- If not, you feel cold or warm.

The Energy Balance



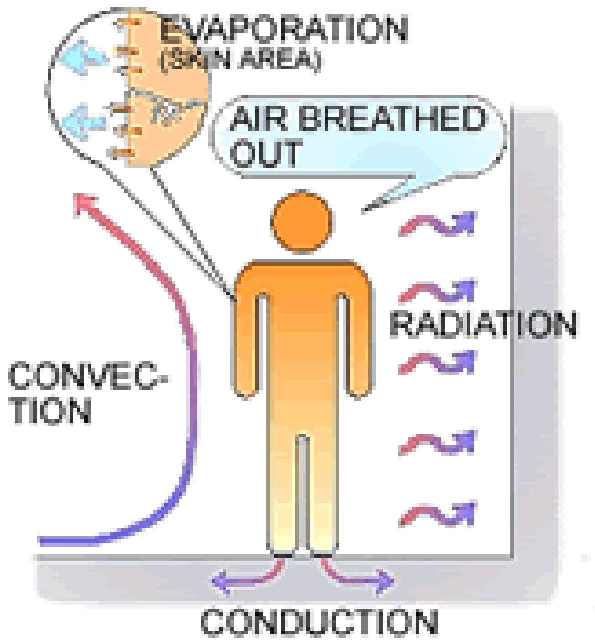
- Thermal Comfort can only be maintained when heat produced by metabolism equals the heat lost from body.

1. Introduction



- General heat balance

$$S = M - W - E - (R + C)$$



where

S = rate of heat storage of human body

M = metabolic rate

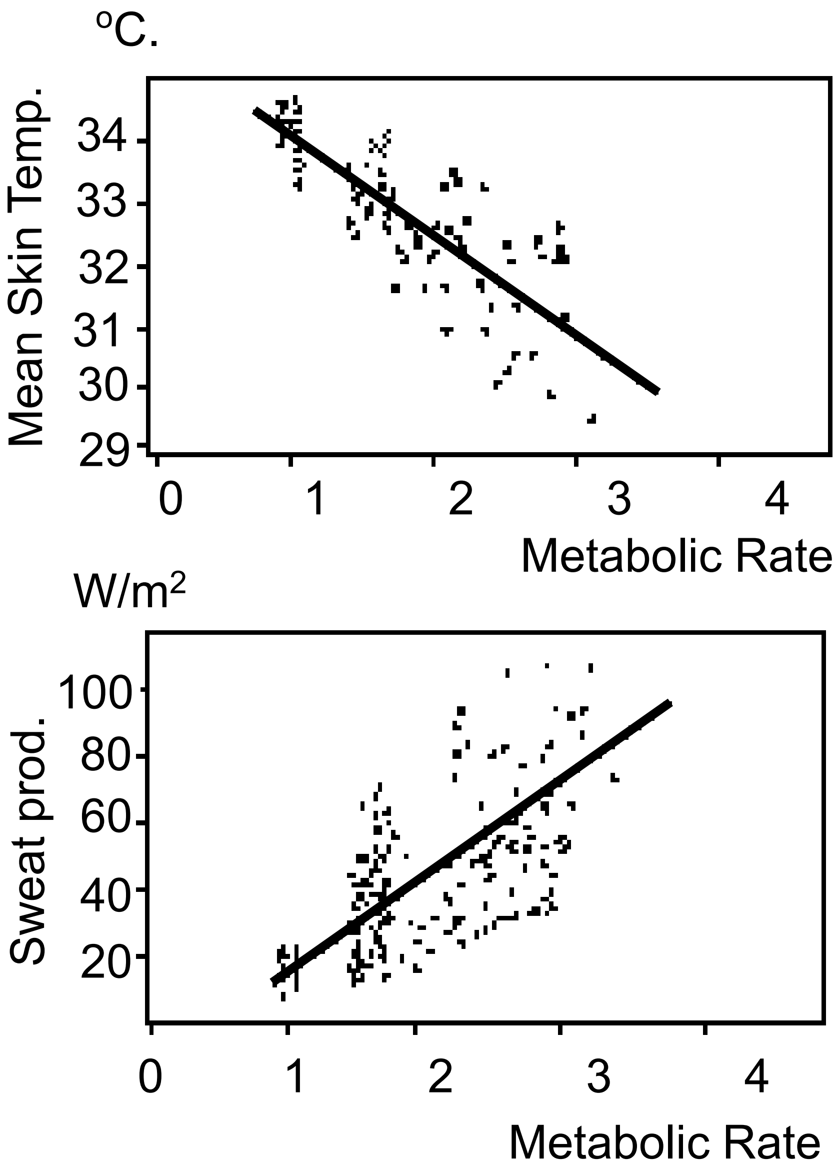
W = mechanical work done by human body

E = rate of total evaporation loss

R + C = dry heat exchange through radiation & convection

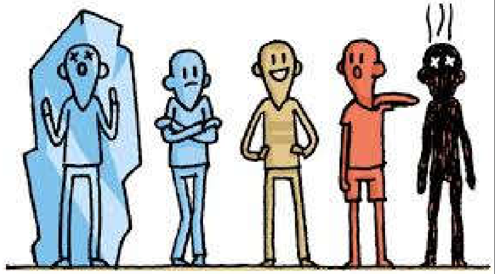
Storage = Production – Loss

Conditions for Thermal Comfort



- Two conditions must be fulfilled to maintain Thermal Comfort:
  - Heat produced must equal heat lost
  - Signals from Heat- and Cold-sensors must neutralise each other
- The sweat production is used instead of body core temperature, as measure of the amount of warm impulses.
- Relation between the parameters found empirically in experiments.
- No difference between sex, age, race or geographic origin.

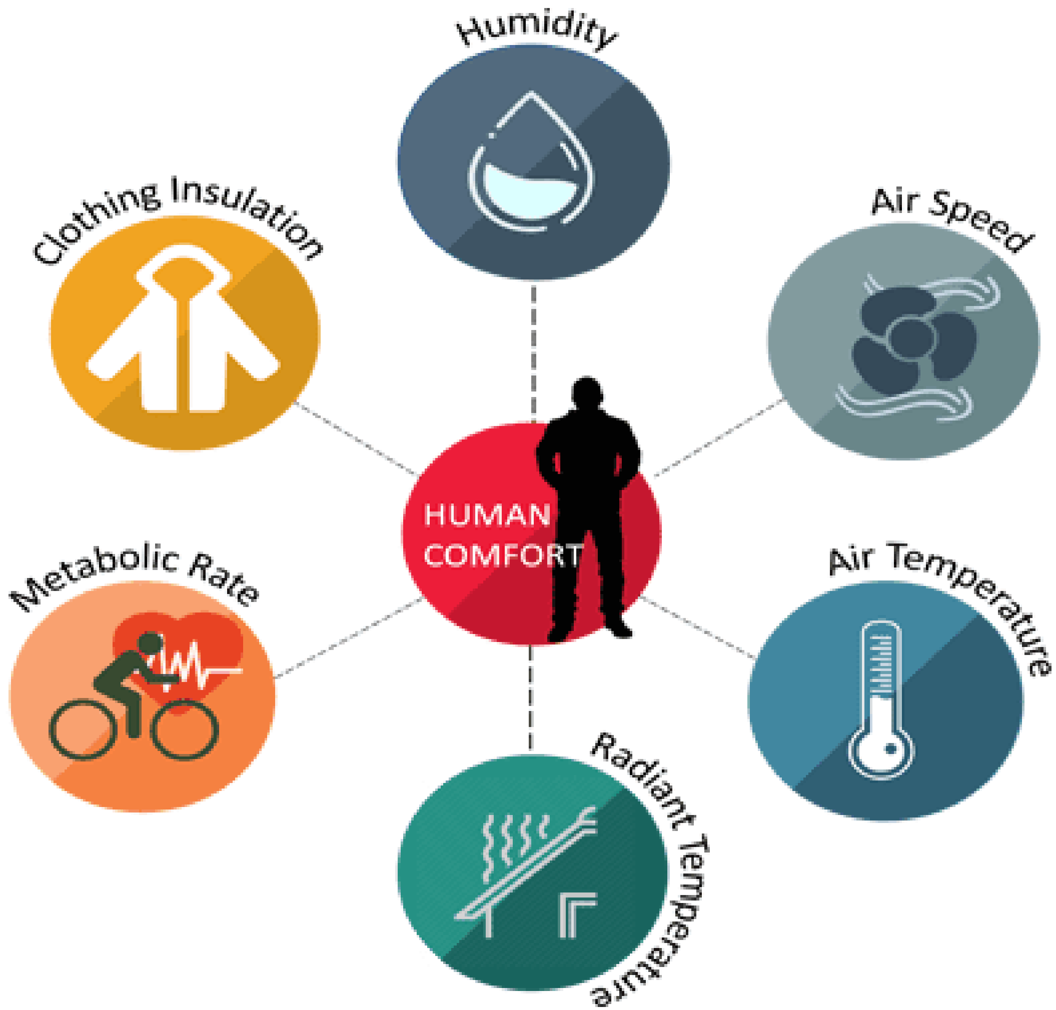
1. Introduction



- BEAM Plus NB2.0 Health and Wellbeing
  - HWB 9 Thermal Comfort
  - (a) Thermal Comfort Analysis
    - 2 credits for conducting thermal comfort analysis and demonstrate that normally occupied spaces can fulfill the thermal comfort requirements.
  - (b) Thermal Comfort Measurement
    - 1 additional BONUS credit for conducting on-site measurements to verify the thermal comfort performance.

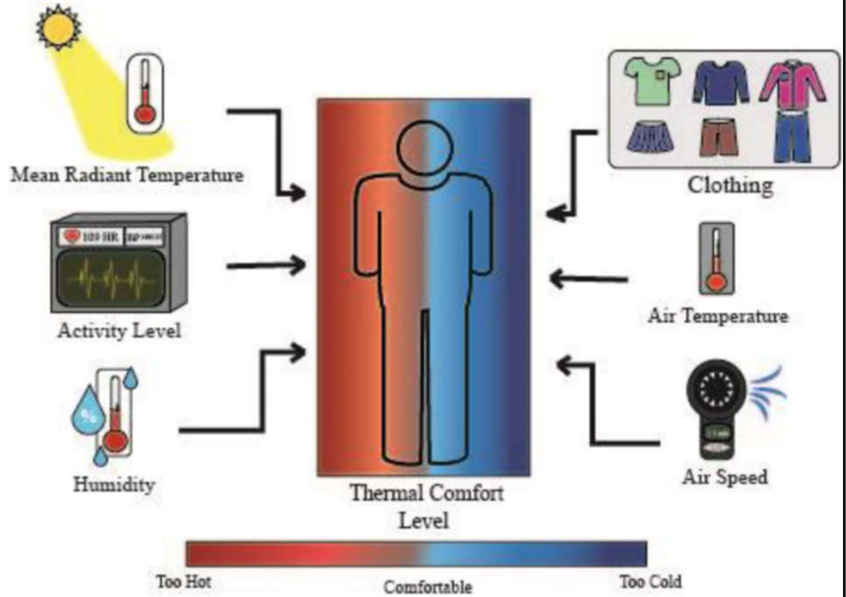
2. Thermal Comfort Prediction

- Six factors for acceptable thermal comfort:
  - Metabolic rate
  - Clothing insulation
  - Air temperature
  - Radiant temperature
  - Air speed
  - Humidity

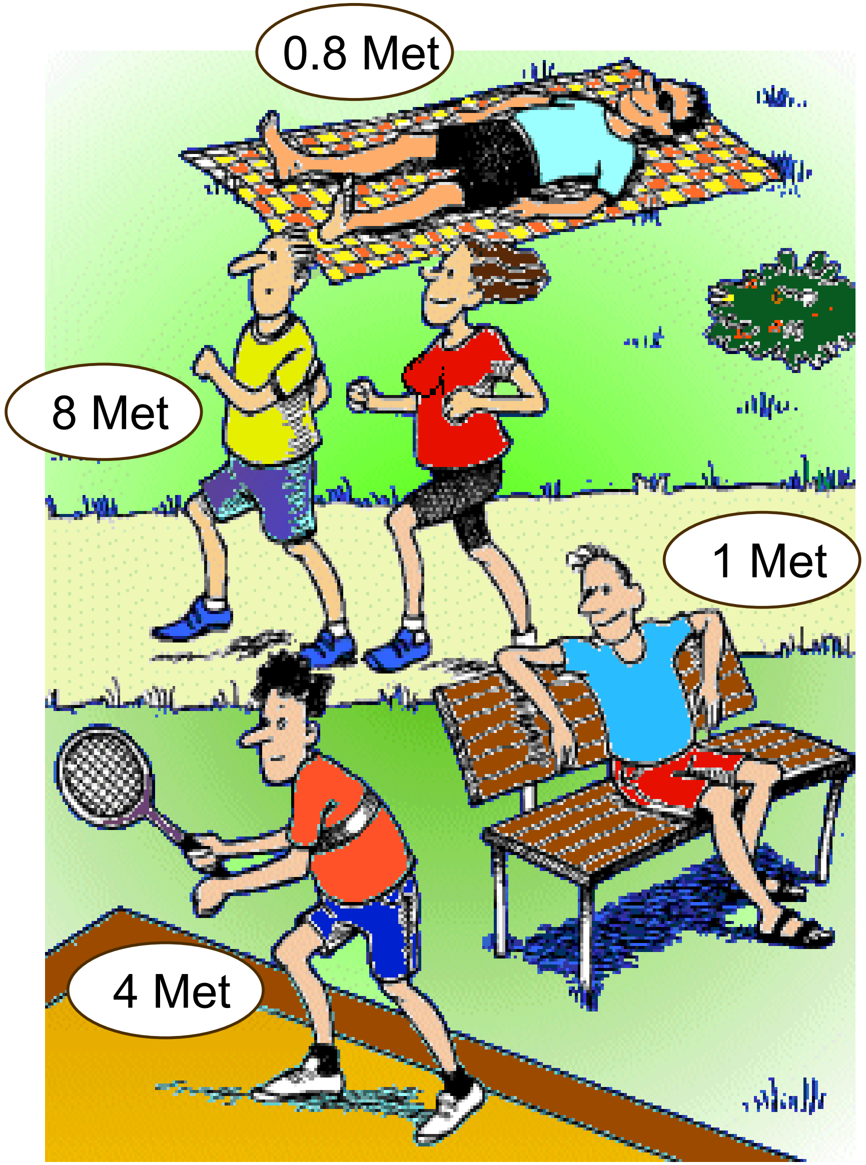


2. Thermal Comfort Prediction

- Personal parameters to estimate and calculate:
  - Met - Estimation of metabolic rate
  - Clo - Calculation of clothing insulation value
- Environmental parameters to measure:
  - t_a - Air temperature
  - t_r - Mean radiant temperature
  - v_a - Air velocity
  - p_a - Humidity



Metabolic Rate



- Energy released by metabolism depends on muscular activity.
- Metabolism is measured in Met (1 Met=58.15 W/m^2 body surface).
- Body surface for normal adult is 1.7 m^2.
- A sitting person in thermal comfort will have a heat loss of 100 W.
- Average activity level for the last hour should be used when evaluating metabolic rate, due to body's heat capacity.

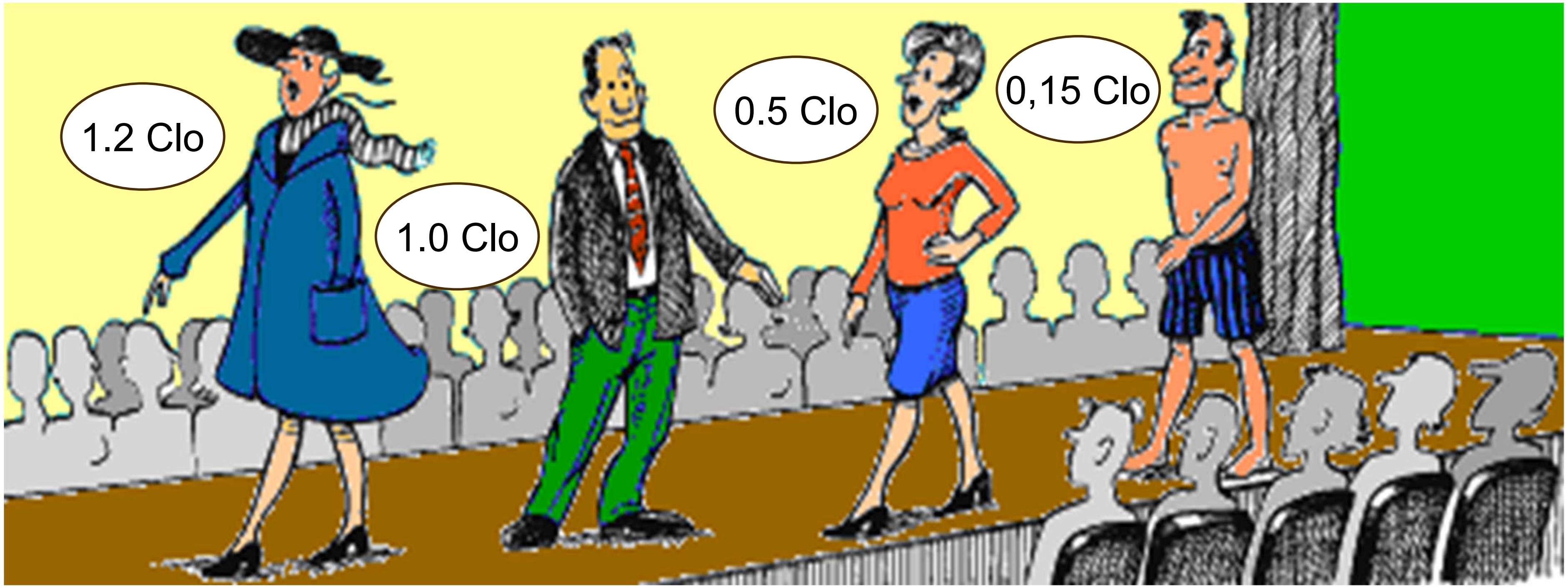
Met Value Table

Activity	Metabolic rates [M]	
Reclining	46 W/m^2	0.8 Met
Seated relaxed	58 W/m^2	1.0 Met
Clock and watch repairer	65 W/m^2	1.1 Met
Standing relaxed	70 W/m^2	1.2 Met
Car driving	80 W/m^2	1.4 Met
Standing, light activity (shopping)	93 W/m^2	1.6 Met
Walking on the level, 2 km/h	110 W/m^2	1.9 Met
Standing, medium activity (domestic work)	116 W/m^2	2.0 Met
Washing dishes standing	145 W/m^2	2.5 Met
Walking on the level, 5 km/h	200 W/m^2	3.4 Met
Building industry	275 W/m^2	4.7 Met
Sports - running at 15 km/h	550 W/m^2	9.5 Met

Met Value Examples

Met Value Examples

Calculation of Insulation in Clothing



- 1 Clo = Insulation value of 0,155 $m^2\ {}^oC/W$

Clo Values Table

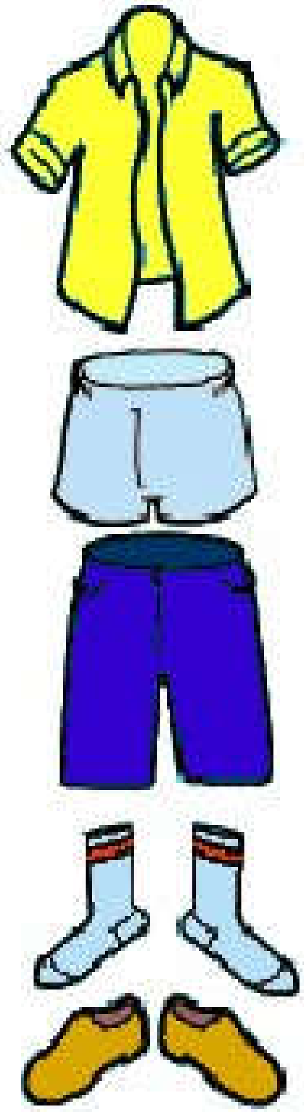
Garment description		I_{clu} Clo	I_{clu} m^2 °C/W
Underwear	Pantyhose Briefs Pants long legs	0.02 0.04 0.10	0.003 0.006 0.016
Underwear, shirts	Bra T-shirt Half-slip, nylon	0.01 0.09 0.14	0.002 0.014 0.022
Shirts	Tube top Short sleeves Normal, long sleeves	0.06 0.09 0.25	0.009 0.029 0.039
Trousers	Shorts Normal trousers Overalls	0.06 0.25 0.28	0.009 0.039 0.043
Insulated coveralls	Multi-component filling Fibre-pelt	1.03 1.13	0.160 0.175
Sweaters	Thin sweater Normal sweater Thick sweater	0.20 0.28 0.35	0.031 0.043 0.054

Clo Values Table

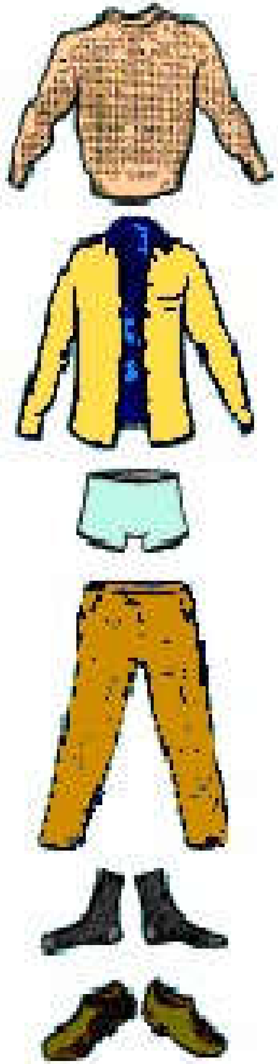
Garment description		I_{clu} Clo	I_{clu} m^2 °C/W
Jackets	Vest Jacket	0.13 0.35	0.020 0.054
Coats over-trousers	Coat Parka Overalls	0.60 0.70 0.52	0.093 0.109 0.081
Sundries	Socks Shoes (thin soled) Boots Gloves	0.02 0.02 0.10 0.05	0.003 0.003 0.016 0.008
Skirt, dresses	Light skirt, 15cm above knee Heavy skirt, knee-length Winter dress, long sleeves	0.10 0.25 0.40	0.016 0.039 0.062
Sleepwear	Shorts Long pyjamas Body sleep with feet	0.10 0.50 0.72	0.016 0.078 0.112
Chairs	Wooden or metal Fabric-covered, cushioned Armchair	0.00 0.10 0.20	0.000 0.016 0.032

Calculation of Clo-value (Clo)

Insulation for the entire clothing: $I_{cl} = \sum I_{clu}$



$$
\begin{array}{r}
0.19 \\
+ \\
0.04 \\
+ \\
0.11 \\
+ \\
0.02 \\
+ \\
\underline{0.02} \\
0.38
\end{array}
$$



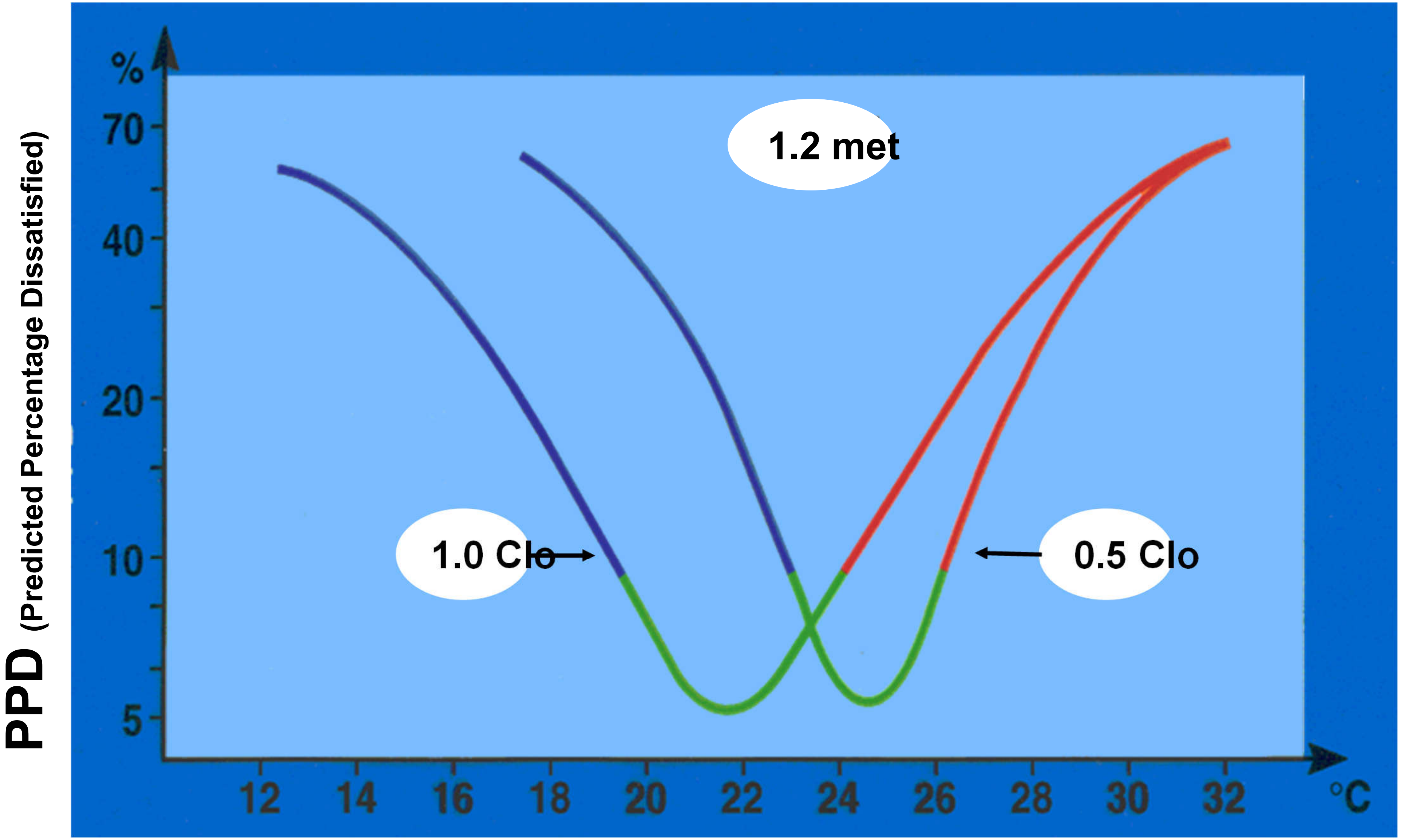
$$
\begin{array}{r}
0.28 \\
+ \\
0.25 \\
+ \\
0.04 \\
+ \\
0.25 \\
+ \\
0.05 \\
+ \\
\underline{0.04} \\
0.91
\end{array}
$$

Things to consider when calculation the CLO value

Thermal insulation of chairs

Insulation of wet clothing

Adjustment of Clo Value

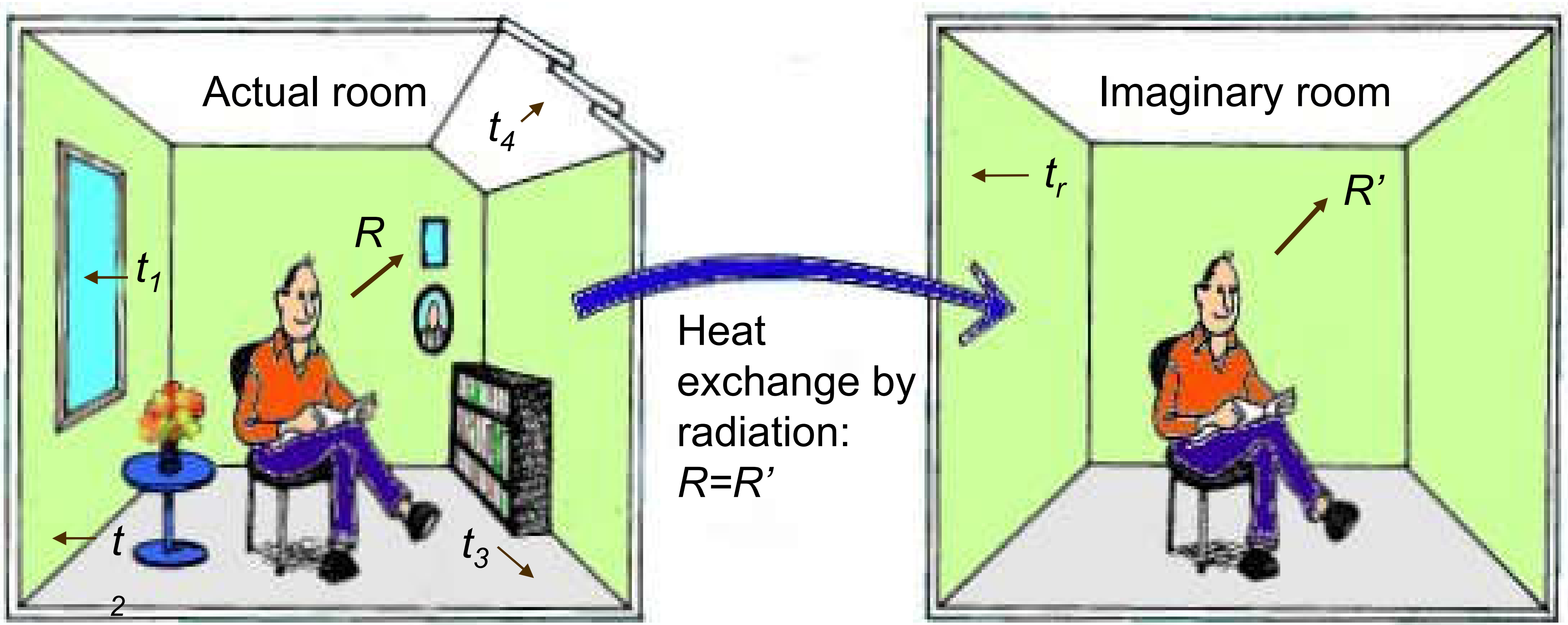


Operative Temperature

2. Thermal Comfort Prediction

- Environmental factors:
  - Dry-bulb temperature (also related to humidity)
  - Relative humidity (or water vapour pressure)
    - Influences evap. heat loss and skin wettedness
    - Usually RH between 30% and 70% is comfortable
  - Air velocity (increase convective heat loss)
    - Preferable air velocity
  - Mean radiation temperature
    - Radiation has great effect on thermal sensation

Mean Radiant Temperature



- The Mean Radiant Temperature is that uniform temperature of an imaginary black enclosure resulting in same heat loss by radiation from the person, as the actual enclosure.
- Measuring all surface temperatures and calculation of angle factors is time consuming. Therefore use of Mean Radiant Temperature is avoided when possible.

The Comfort Equation

Comfort Equation:

$$M - W = H + E_c + C_{res} + E_{res}$$

$$E_c = 3.05 \cdot 10^{-3} \cdot \left[5733 - 6.99 \cdot (M - W - P_a \right] + 0.42 \cdot \left(M - W - 58.15 \right)$$

$$C_{res} = 0.0014 \cdot M \cdot \left(34 - t_a \right)$$

$$E_{res} = 1.72 \cdot 10^{-5} \cdot M \cdot \left(5867 - P_a \right)$$

H is either measured directly or calculated

The Comfort Equation (cont'd)

What to measure

Air Temperature + Mean Radiant Temperature
+ Air Velocity + Humidity

OR

Operative Temperature + Air Velocity + Humidity

OR

Equivalent Temperature + Humidity

What to estimate

MET - VALUE (Metabolism)
CLO - VALUE (Clothing level)

2. Thermal Comfort Prediction

- Fanger's comfort criteria
  - Developed by Prof. P. O. Fanger (Denmark)
  - **Fanger's comfort equation**:

$$f\,(M,\, I_{cl},\, V,\, t_r,\, t_{db},\, P_s) = 0$$

where M = metabolic rate (met)

I_{cl} = cloth index (clo)

V = air velocity (m/s)

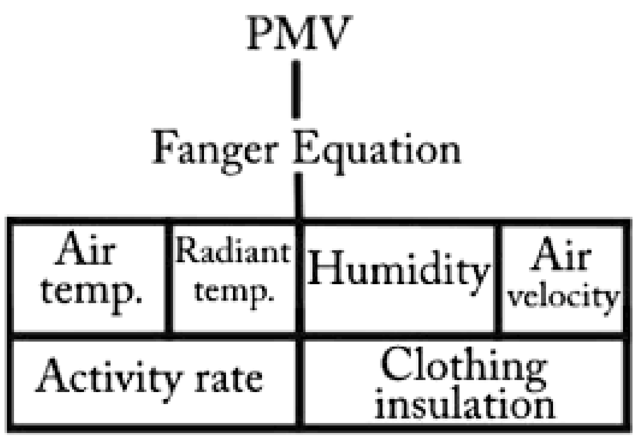
t_r = mean radiant temp. (^{o}C)

t_{db} = dry-bulb temp. (^{o}C)

P_s = water vapour pressure (kPa)

2. Thermal Comfort Prediction

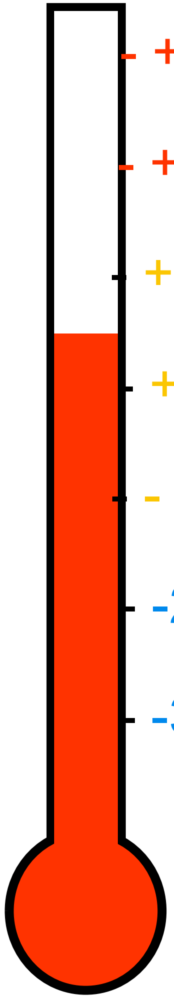
- Fanger's equation is complex
  - But it may be transformed to comfort diagrams
  - It can also be used to yield three indices:
    - Predicted mean vote (PMV)
    - Predicted percentage of dissatisfied (PPD)
    - Lowest possible percentage dissatisfied (LPPD)



2. Thermal Comfort Prediction

- **Predicted mean vote (PMV)** 預測平均投票
  - A complex function of six major comfort parameters;
  - Predict mean value of the subjective ratings of a group of people in a given environment
- **Predicted percentage of dissatisfied (PPD)** 預測不滿意百分比
  - Determined from PMV as a quantitative measure of thermal comfort
  - 'Dissatisfied' means not voting -1, +1 or 0 in PMV
  - normally, PPD < 7.5% at any location and LPPD < 6%

Predicted Mean Vote scale



+3 Hot

+2 Warm

+1 Slightly warm

+0 Neutral

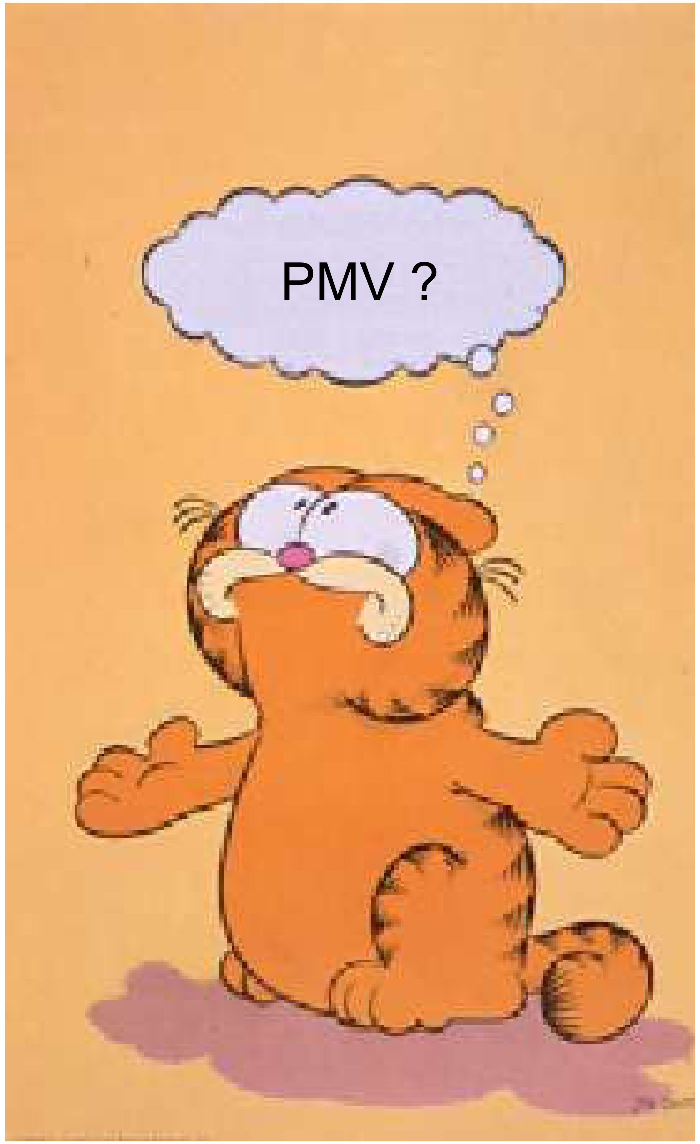
- 1 Slightly cool

-2 Cool

-3 Cold

The PMV index is used to quantify the degree of discomfort

Calculation of PMV index



$$PMV = (0{,}303e^{-2{,}100*M} + 0{,}028)*[(M-W) - H - E_c - C_{res} - E_{res}]$$

$$\Longrightarrow$$

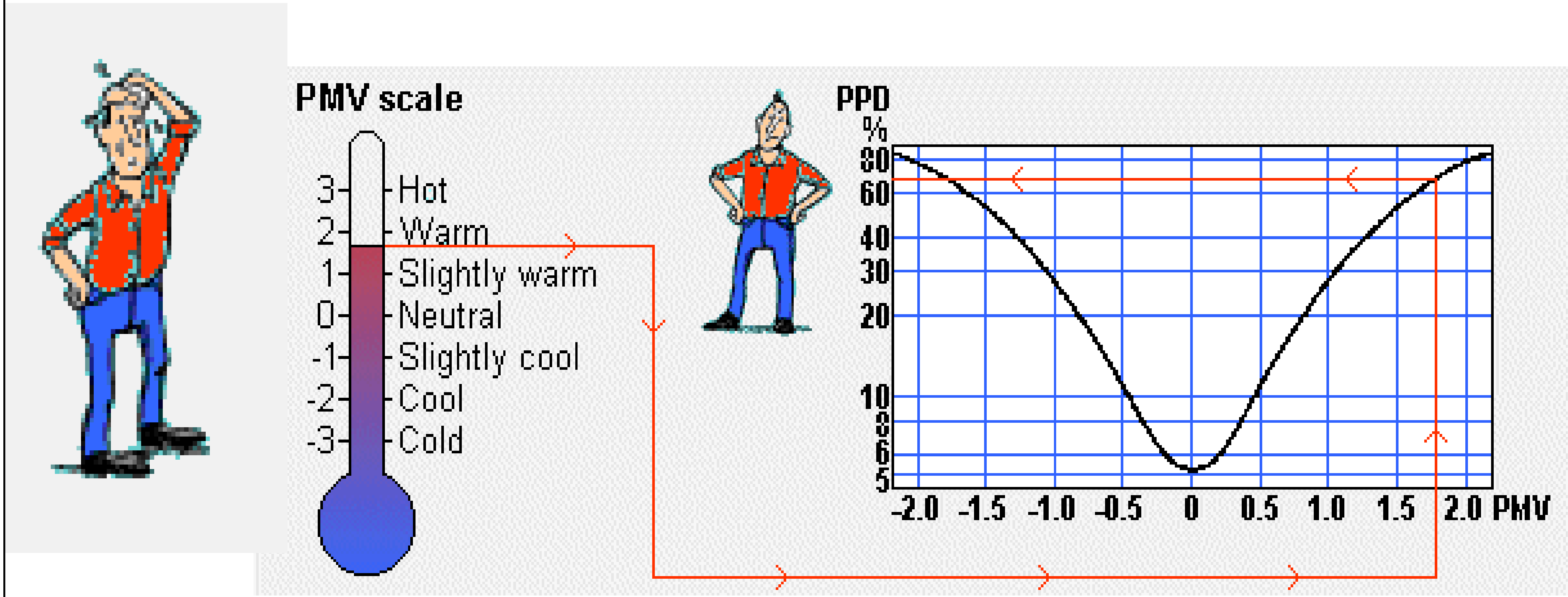
$$PMV = (0{,}303e^{-2{,}100*M} + 0{,}028)*[58{,}15*(M-W)$$
$$-3{,}05*10^{-3}*[5733-406{,}7*(M-W)-p_a]-24{,}21*[(M-W)-1]$$
$$-10^{-3}*M*(5867-p_a)-0{,}0814*M*(34-t_a)$$
$$-3{,}96*10^{-8}*f_{cl*}[(t_{cl}+273)^4 - (t_{eq}+273)^4] - f_{cl}*h_{c,eq}*(t_{cl}-t_{eq})]$$

$$h_{c,eq} = 2{,}38*(t_{cl} - t_{eq})^{0{,}25} \qquad f_{cl}\begin{cases} 1{,}00+0{,}2*I_{cl} \text{ for } I_{cl} < 0{,}5 \text{ clo} \\ 1{,}05+0{,}1*I_{cl} \text{ for } I_{cl} > 0{,}5 \text{ clo} \end{cases}$$

M [MET)]

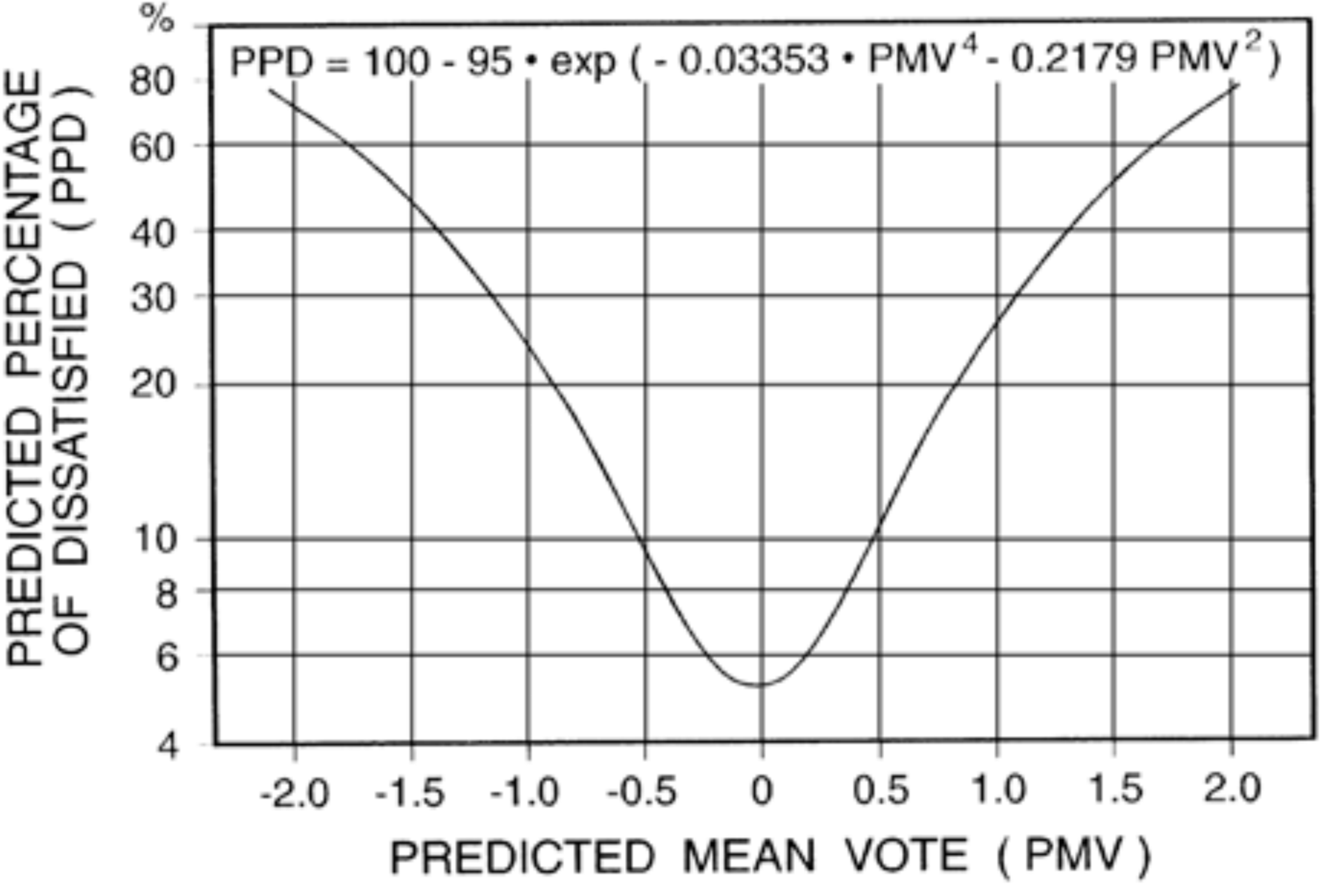
Icl [CLO]

PMV and PPD



- PMV-index (Predicted Mean Vote) predicts the subjective ratings of the environment in a group of people.
  - 0 = neutral (still 5% people are dissatisfied)
- PPD-index predicts the number of dissatisfied people.

Predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV)



(Source: ASHRAE Standard 55-2013)

3. Environmental Indices

- Environmental index
  - Express thermal comfort in a single number by combining 2 or more comfort parameters
- **Operative temperature, t_o**
  - Uniform temp. of an imaginary enclosure with the same dry heat by R + C as in the actual environment
  - Weighted sum of t_{db} and t_r:
    - h_r, h_c: heat transfer coefficients

$$t_o = \frac{h_r \cdot t_r + h_c \cdot t_{db}}{h_r + h_c}$$

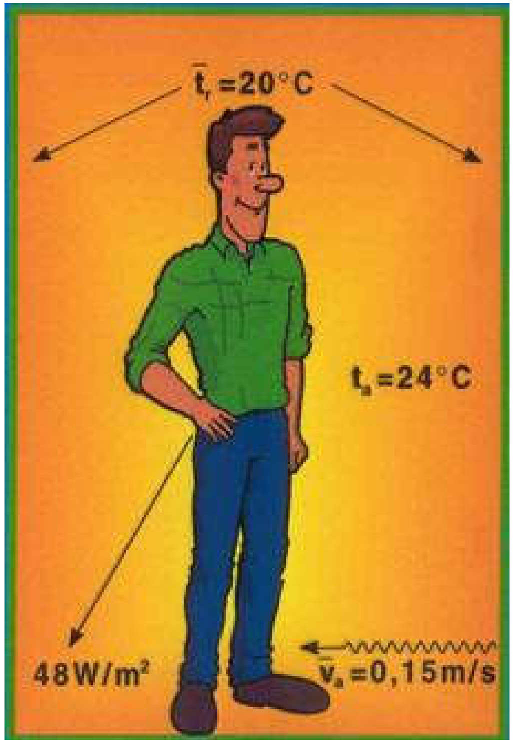
3. Environmental Indices

- **Effective temperature, *ET***
  - Temp. of a still, saturated atmosphere, which would in the absence of radiation, produce the same effect as the atmosphere in question (thus, it combines dry bulb temp. and humidity)
  - Represented by a set of equal comfort lines drawn on the psych chart (see ASHRAE Comfort Zone diagrams)
    - A standard set of thermal conditions representative of typical indoor application is used to define a "standard effective temperature (SET)"

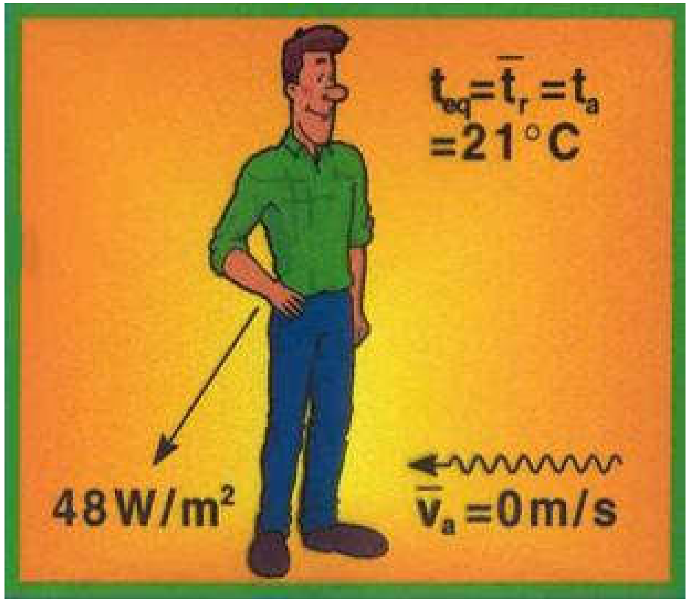
3. Environmental Indices

- **Equaivalent temperature, *EqT***
  - Also called wind chill equivalent temperature, or wind chill index, or wind chill
  - It is the temperature required under no-wind conditions that will equal the cooling effect of the air (the actual air temperature) and the wind on an average size, nude person in the shade
    - Combines dry bulb temp., air velocity & MRT
  - Humidity, presence of sunshine, clothing, and physical activity are not considered (dry heat loss)

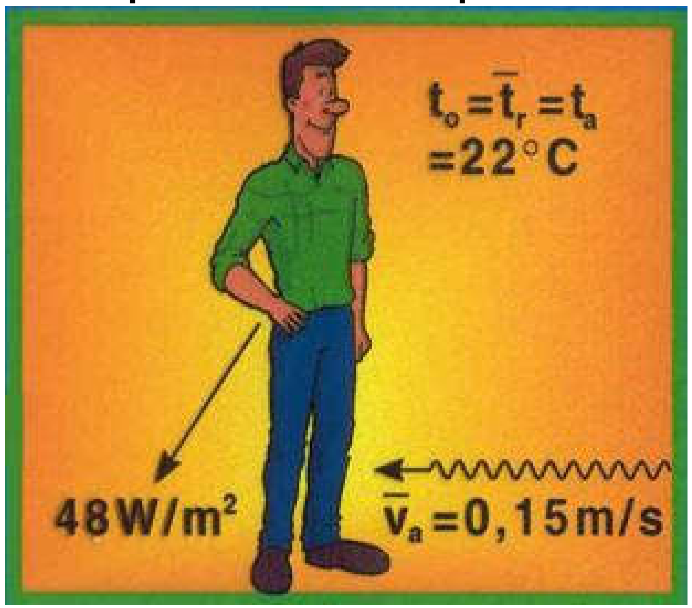
Operative and Equivalent Temperature



Operative temperature



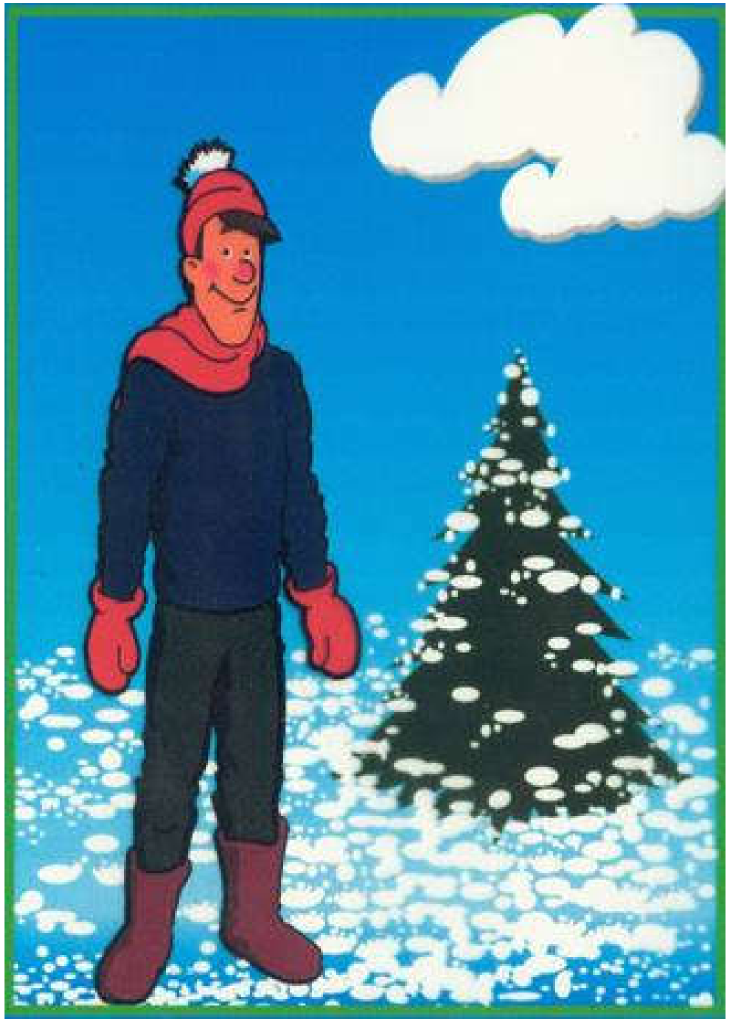
Equivalent temperature



Combines DBT & MRT

Combines DBT, MRT & air velocity

Operative and Equivalent Temperature



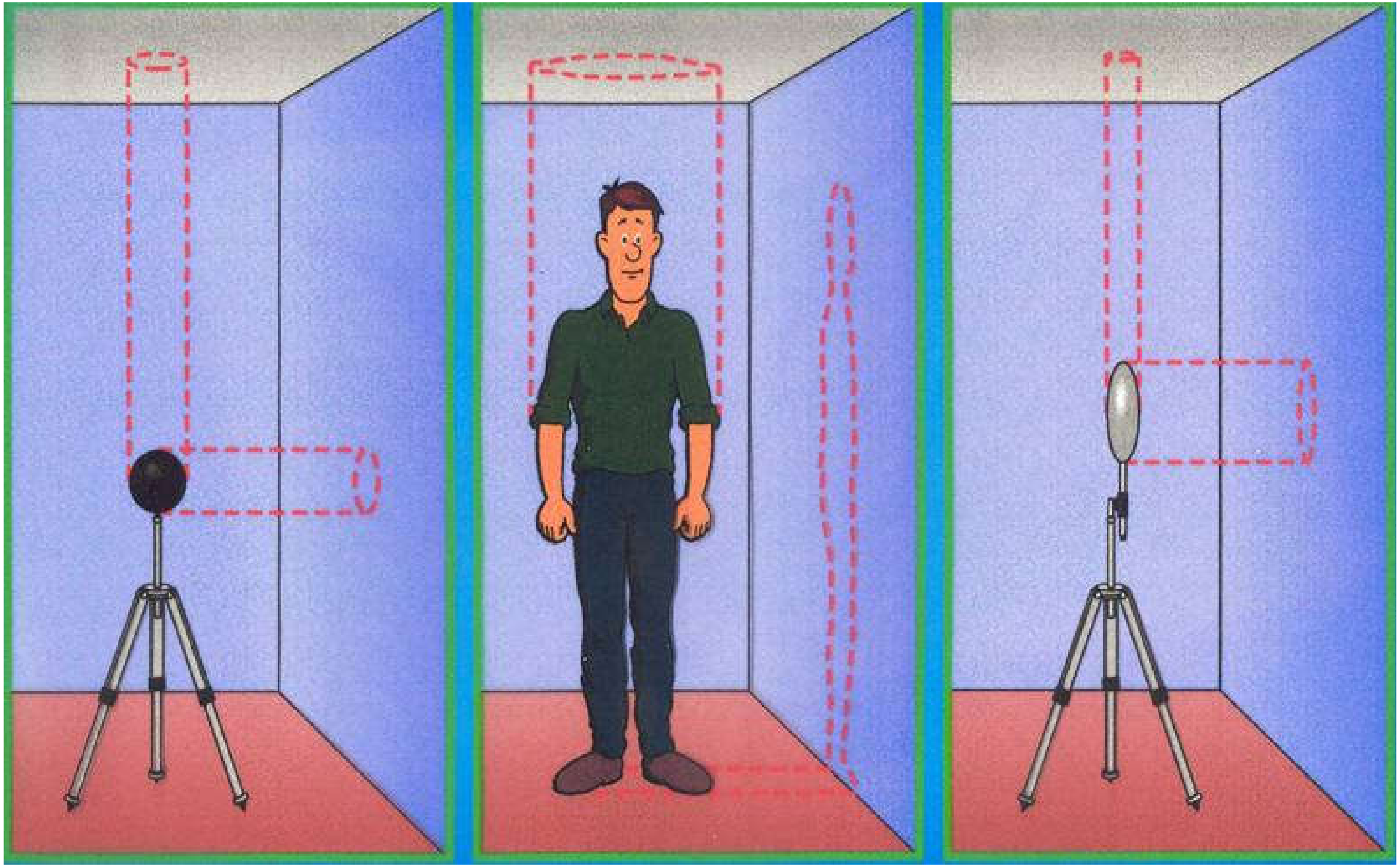
Operative temperature

Combines DBT & MRT

Equivalent temperature

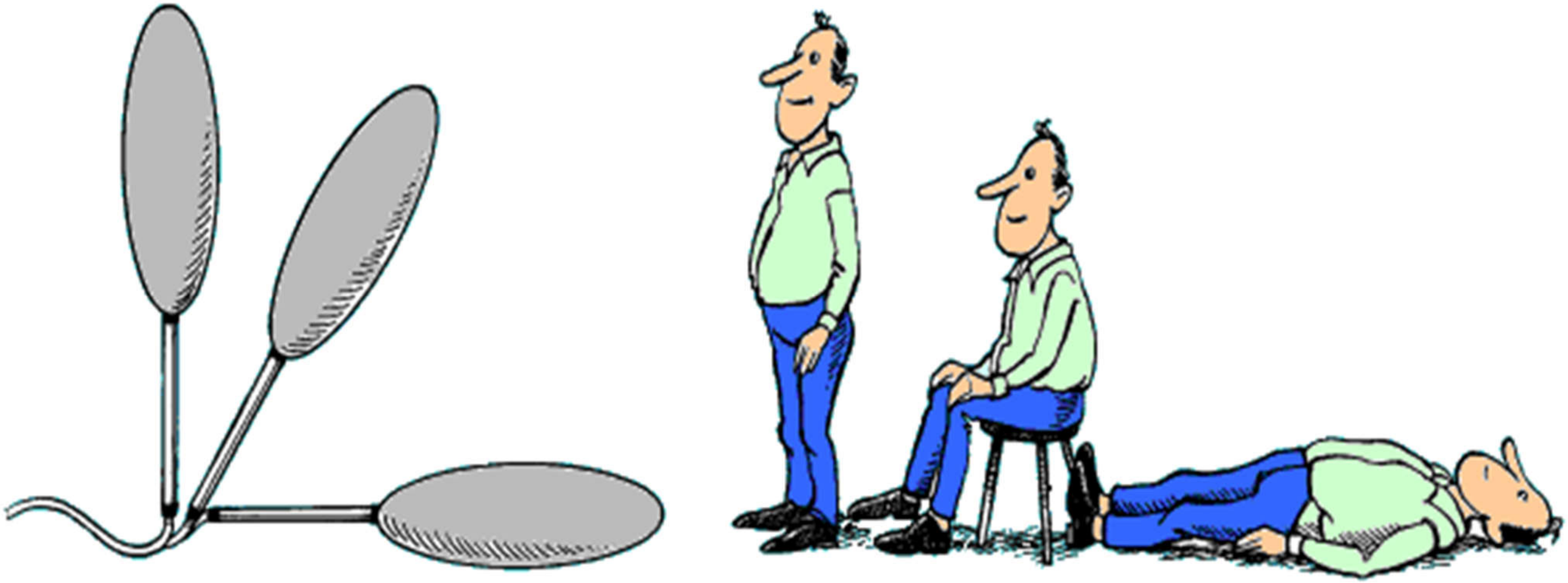
Combines DBT, MRT & air velocity

Projected area factor



$\bar{t}_r = 20\ ^\circ C$ $\bar{t}_r = 20\ ^\circ C$ $\bar{t}_r = 20\ ^\circ C$

Operative Temperature



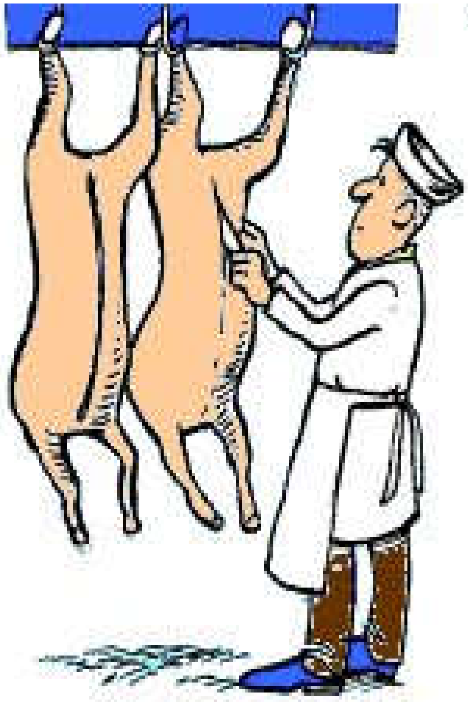
- The Operative temperature t_o integrates the effect of t_a and t_r

- Measure Operative Temperature: the transducer must have same heat exchange properties as an <u>unheated</u> mannequin (artificial human) dummy.

Dry Heat Loss or Equivalent Temperature

- Dry Heat Loss or equivalent temperature can be measured directly, using a heated Operative Temperature shaped transducer.
- The Equivalent temperature t_{eq} integrates the effect of $t_{a,}$ t_r and v_a
- The Dry Heat Loss transducer is heated to the same temperature as the surface temperature of a person's clothing.

Comfort Temperature, t_{co} (typical)

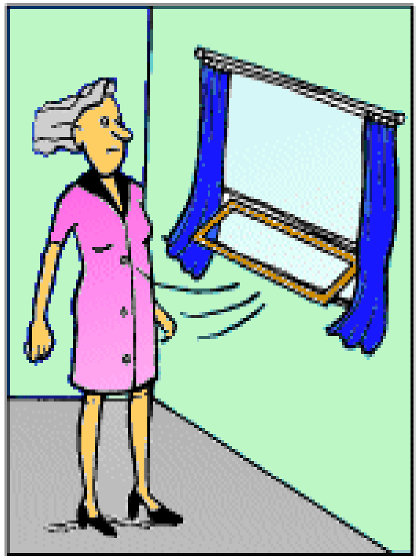


1.7 clo
2.5 Met
RH=50%
t_{co}=6°C

0.8 clo
2.2 Met
RH=50%
t_{co}=18°C

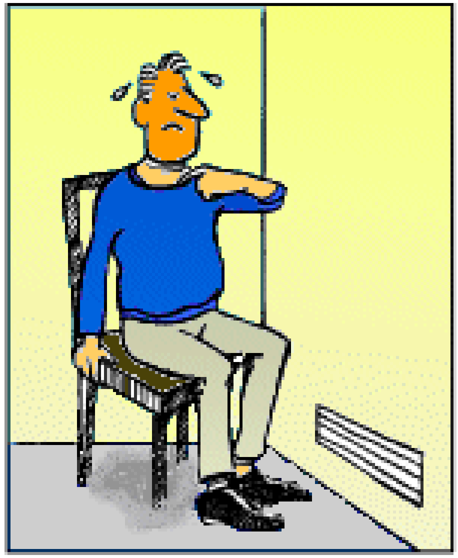
0.5 clo
1.2 Met
RH=50%
t_{co}=24,5°C

Local Thermal Discomfort

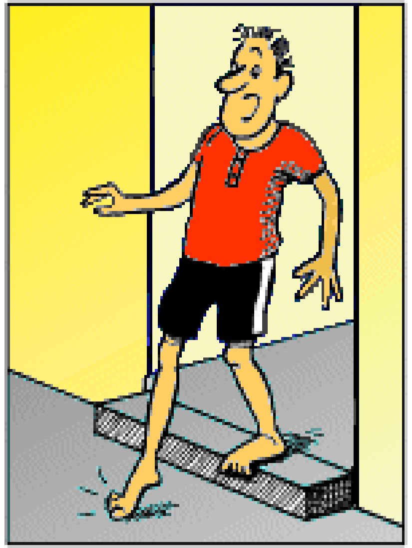


- Draught

- Radiation Asymmetry

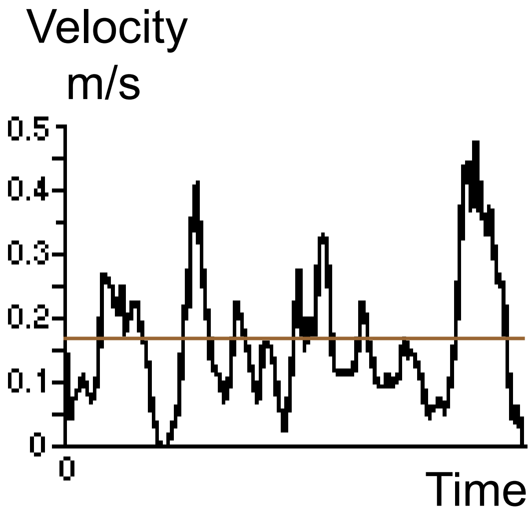


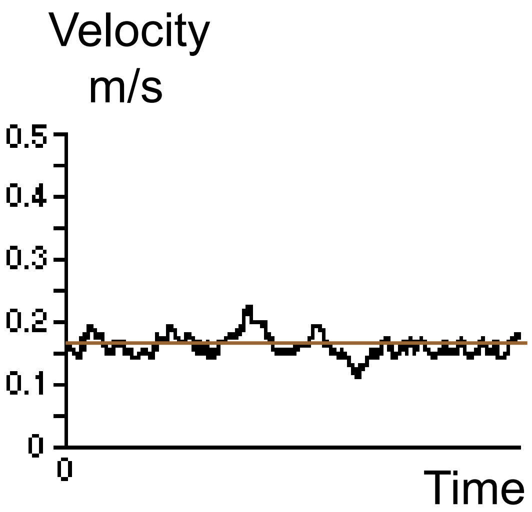
- Vertical Air Temperature Differences.

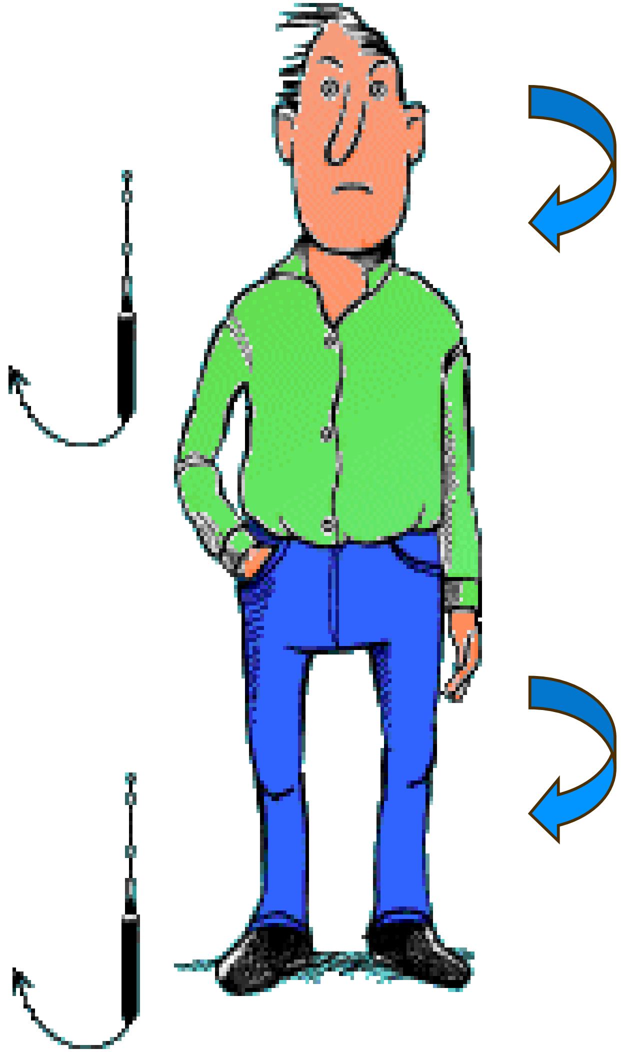


- Floor temperature

Draught

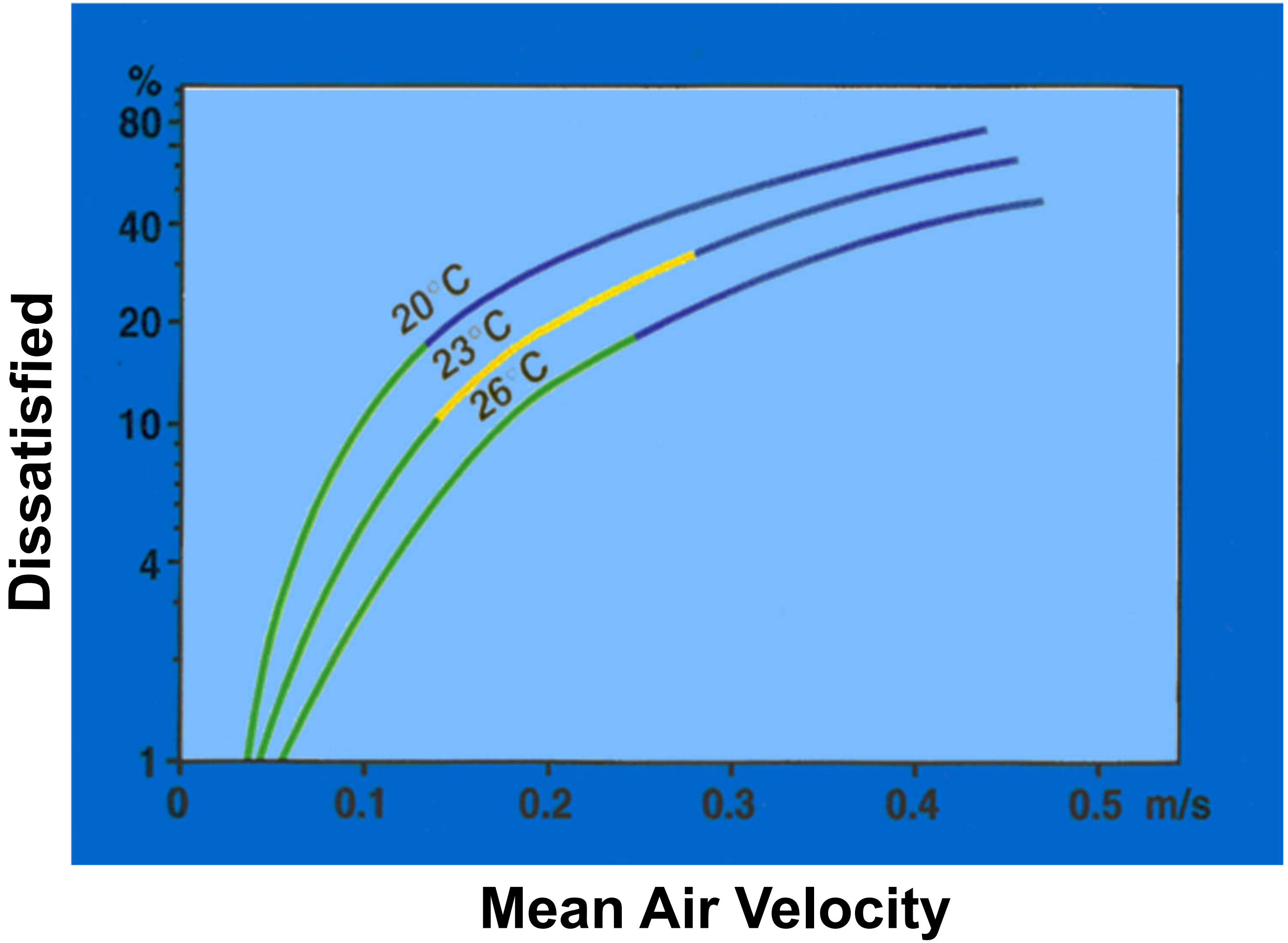






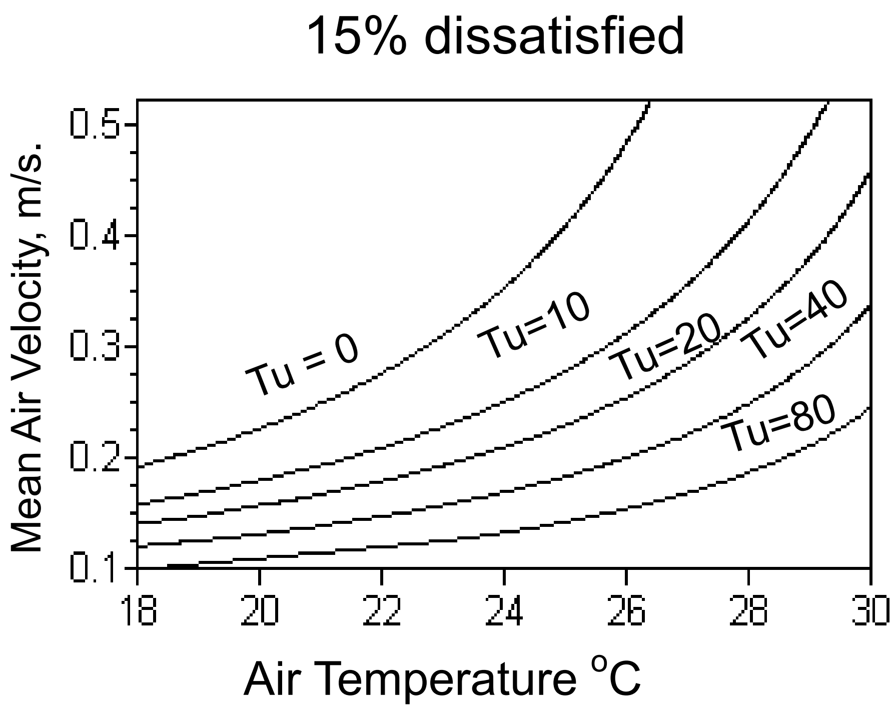
- Draught is the most common complaint indoors
- What is felt is Heat Loss
- Heat Loss is depending on average Air Velocity, Temperature and Turbulence
- High Turbulence is more uncomfortable, even with the same Heat Loss

Draught

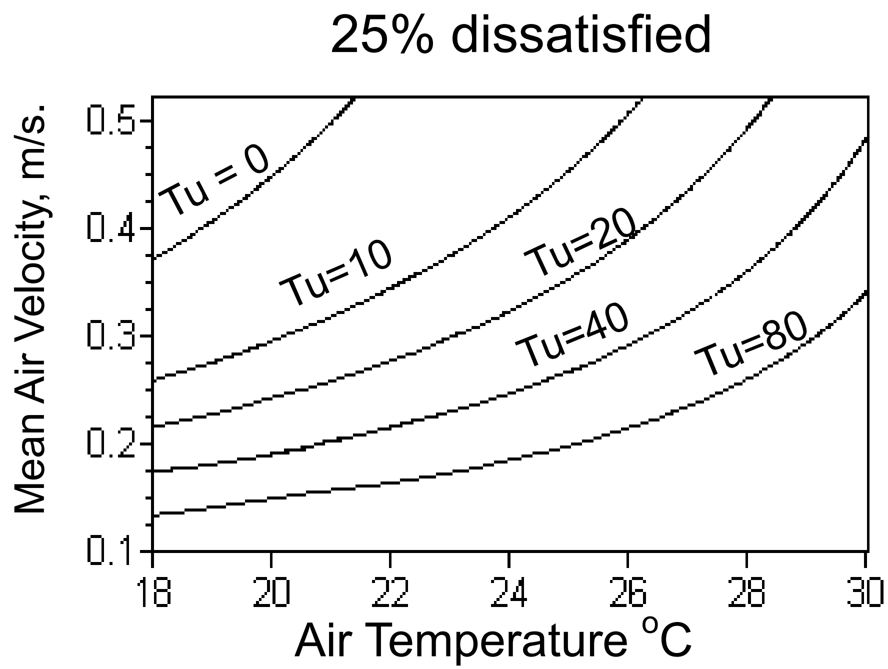


- The sensation of Draught depends on the air temperature
- At lower air temperatures a higher number will be dissatisfied

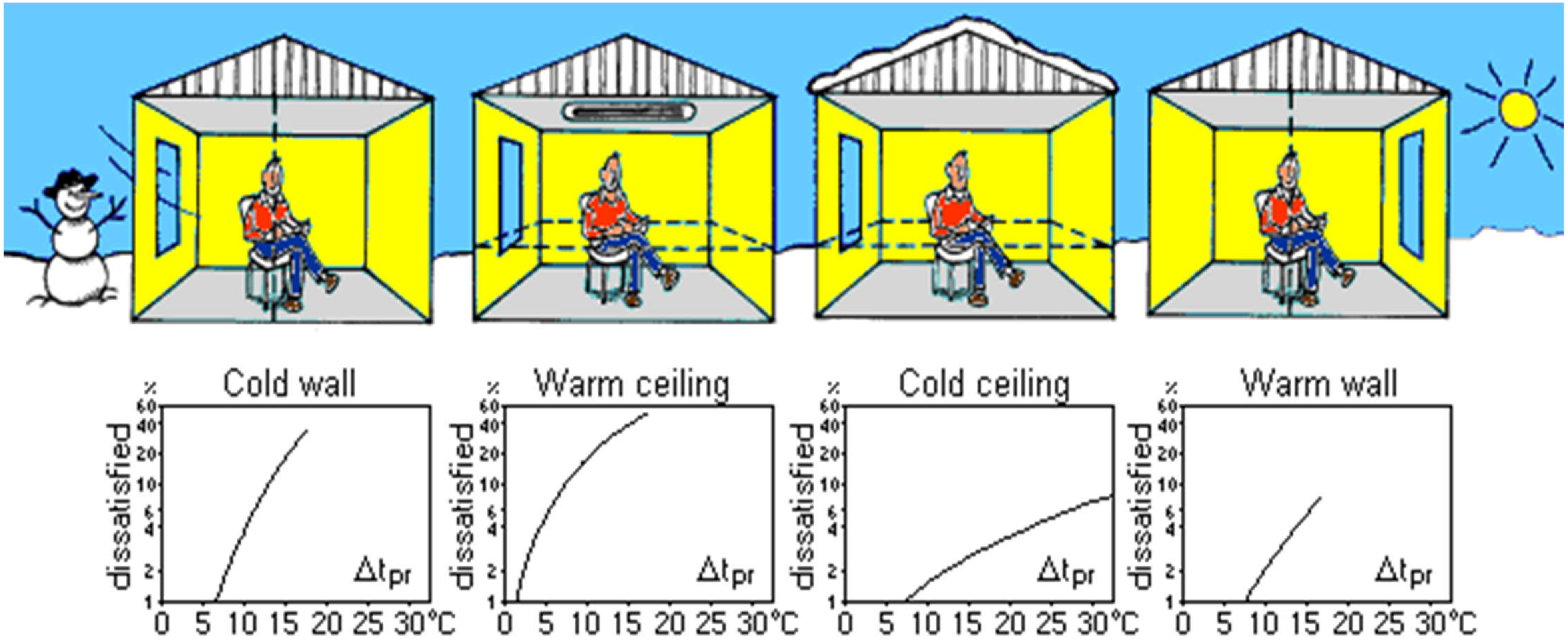
Evaluating Draught Rate



- Fluctuations in Air Velocity is described by Turbulence Intensity (Tu)
- Draught Rate equation is based on studies of 150 people, and stated in ISO 7730

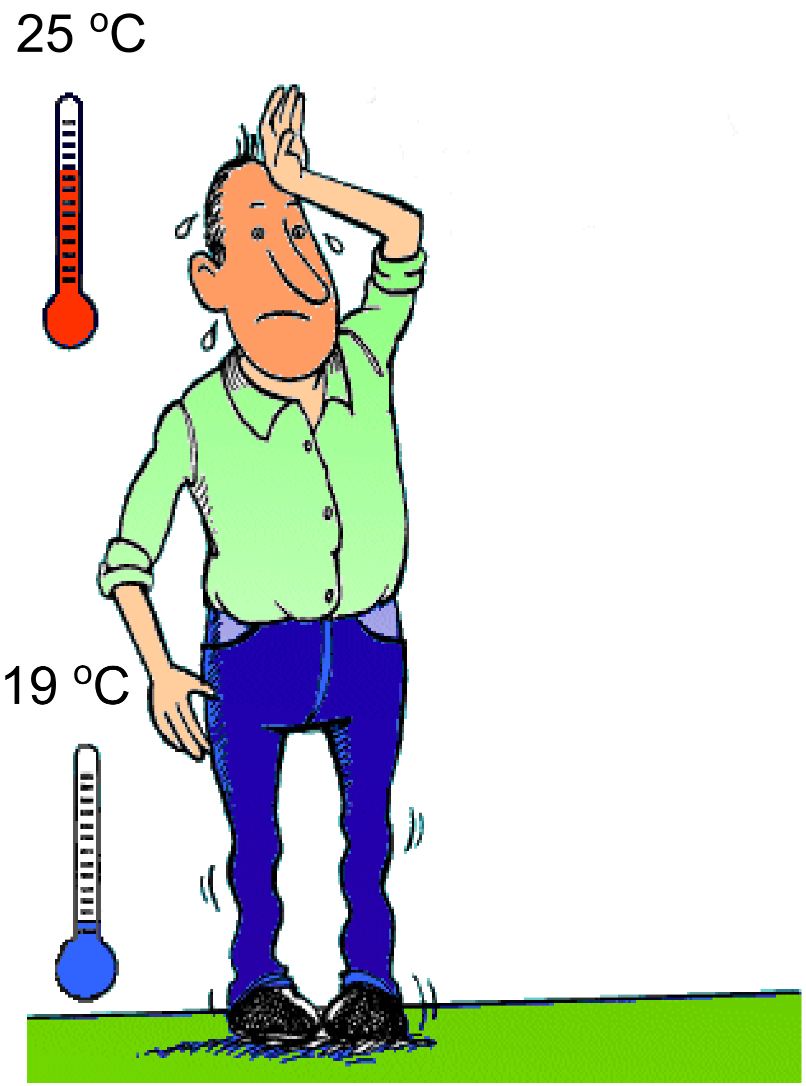


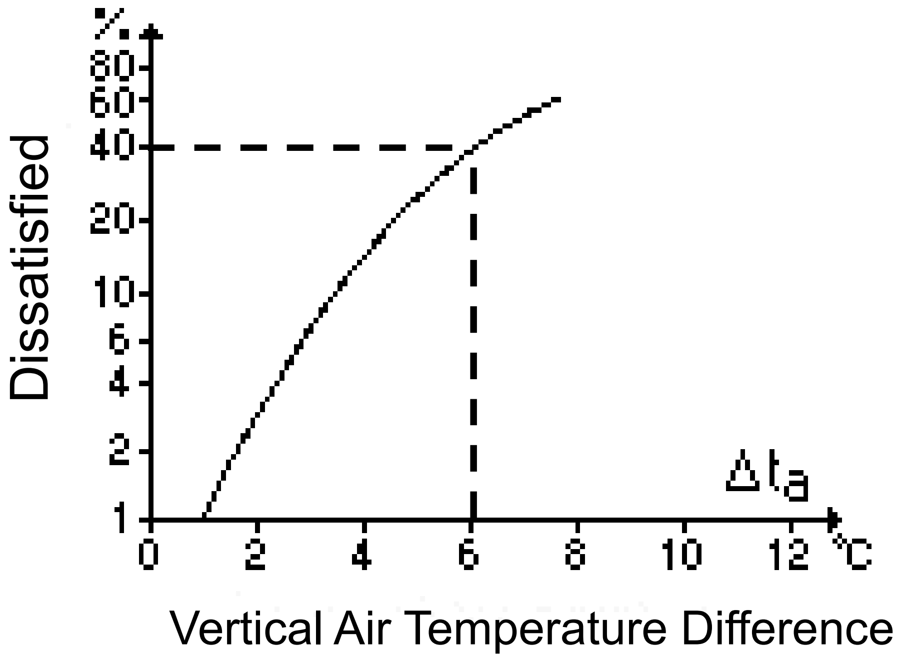
Radiation Asymmetry



- Radiant Temperature Asymmetry is perceived uncomfortable
- Warm ceilings and cold walls causes greatest discomfort

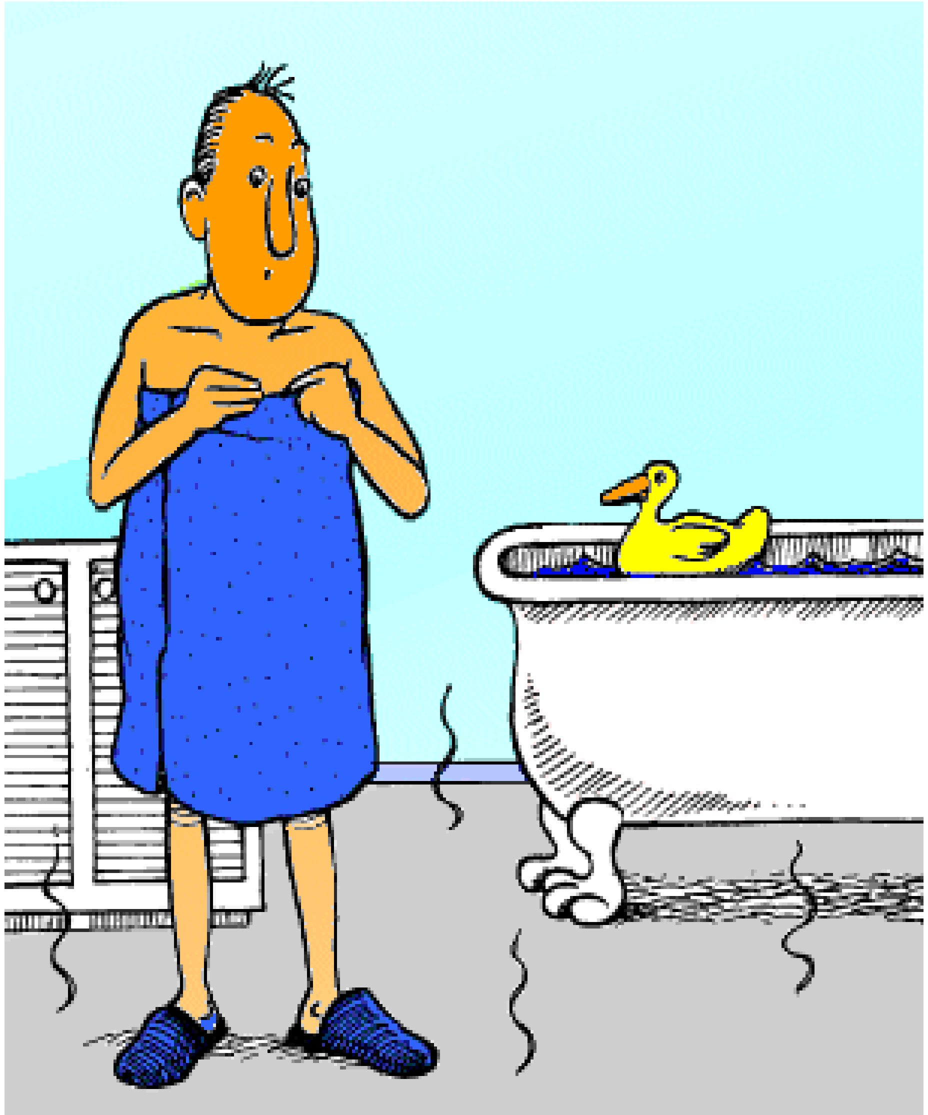
Vertical Air Temperature Difference

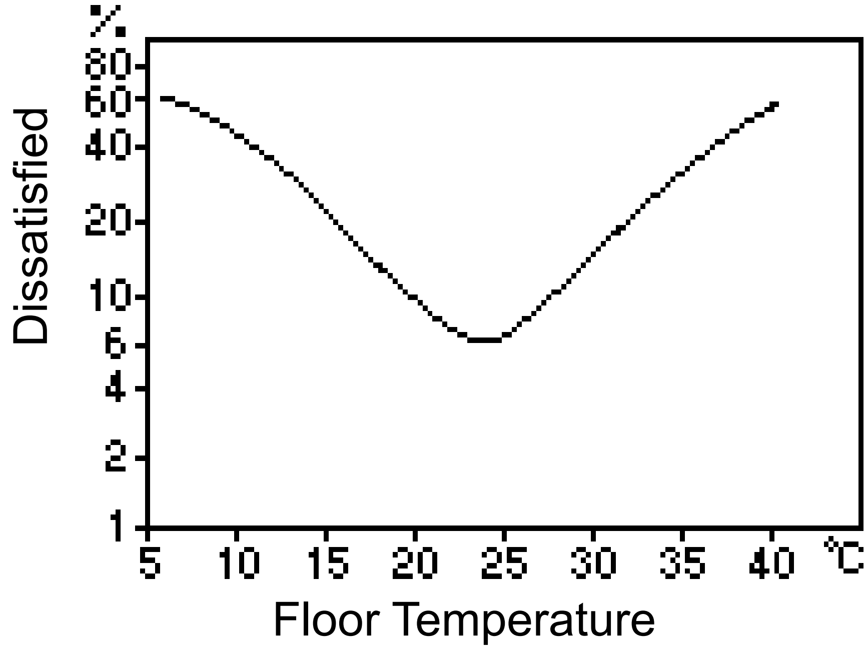




- Vertical Air Temperature Difference is the difference between Air Temperature at ankle and neck level

Floor Temperature





- Acceptable floor temperatures ranging from 19 to 29 ^{o}C
- The graph is made on the assumption that people wear "normal indoor footwear"

Workplace Measurements

- 1.1 m

- 0.6 m

- 0.1 m

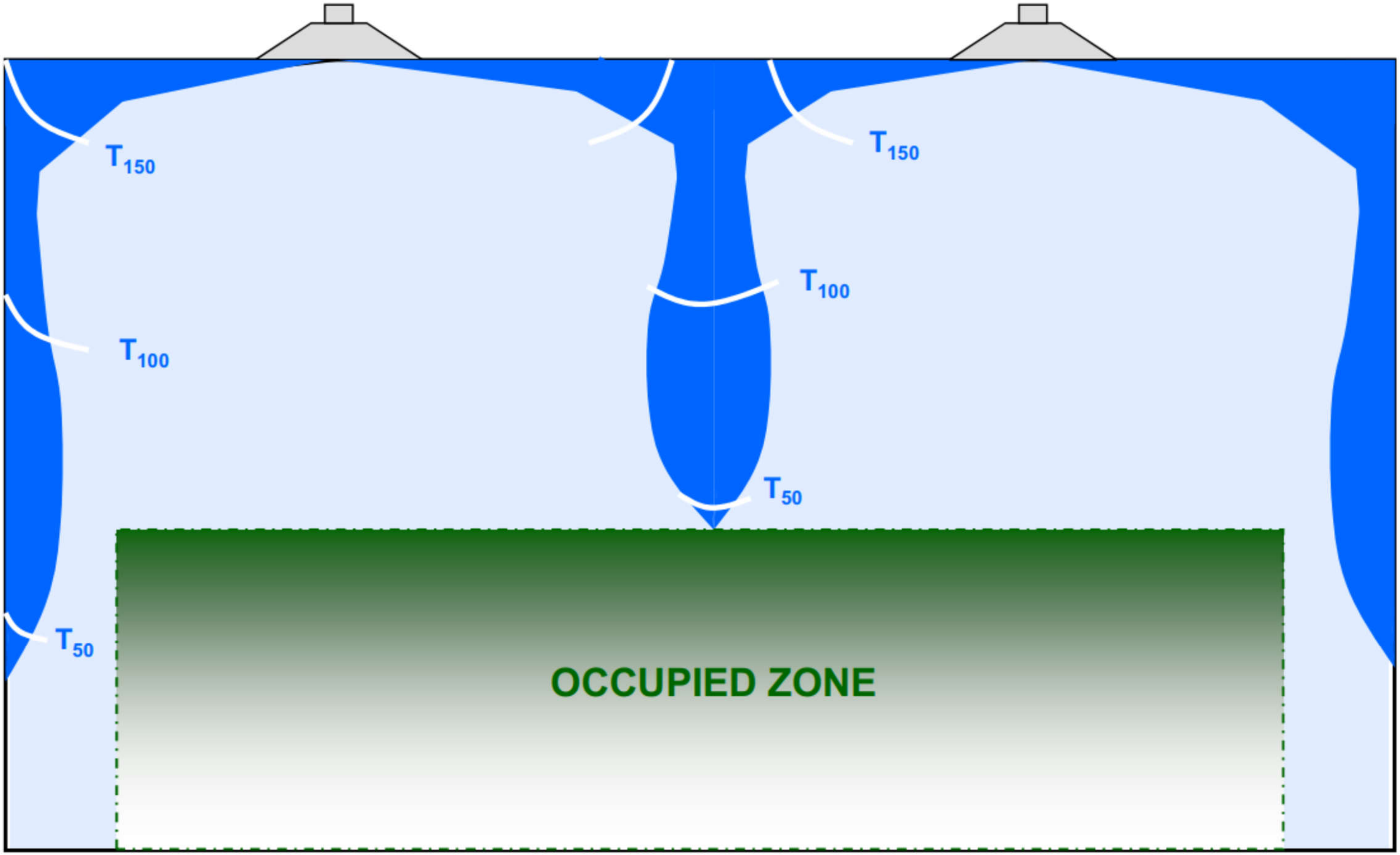
- 1.7 m

- 1.1 m

- 0.1 m

• Measurements of Vertical Temp. difference and Draught at ankle and neck
• Other measurements should be performed at persons centre of gravity

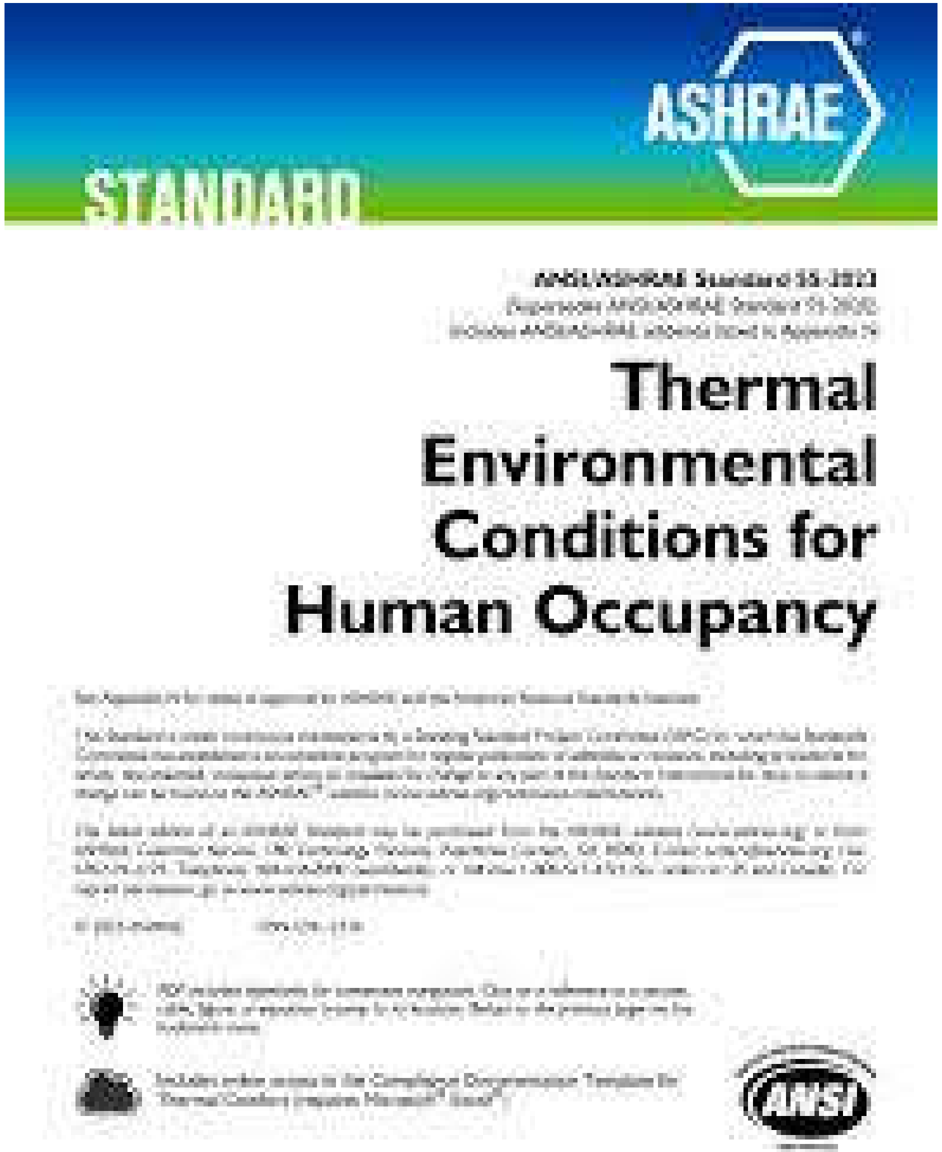
Mixed air systems and occupied zone

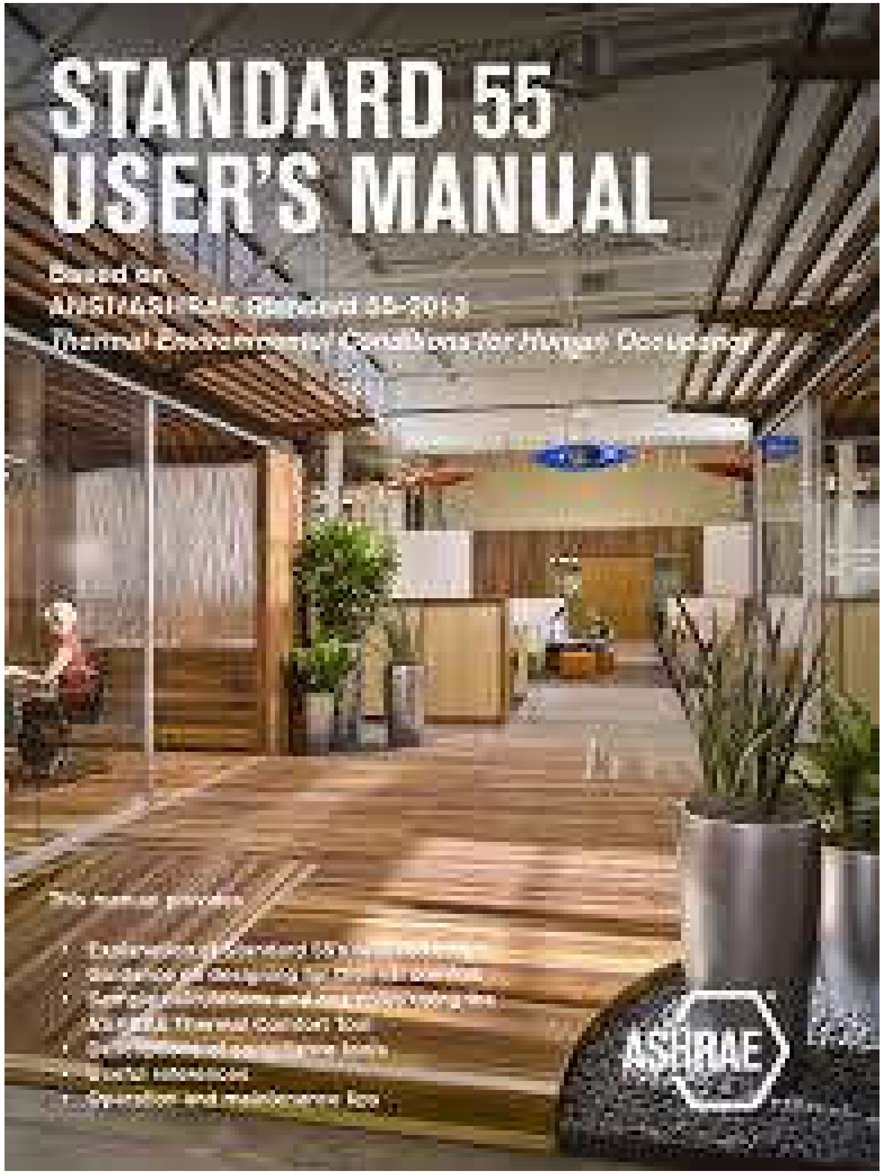


4. ASHRAE Standard 55

- ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy
  - Specifies conditions for acceptable thermal environments and is intended for use in design, operation, and commissioning of buildings and other occupied spaces
  - Provides minimum requirements for acceptable thermal indoor environments

ANSI/ASHRAE Standard 55-2023 and User's Manual





(Source: ASHRAE Standard 55-2023)

4. ASHRAE Standard 55

- Organization of the standard
  - Foreword
  - 1. Purpose
  - 2. Scope
  - 3. Definitions
  - 4. General requirements
  - 5. Conditions that provide thermal comfort
  - 6. Design compliance
  - 7. Evaluation of comfort in existing buildings
  - 8. References

4. ASHRAE Standard 55

- Organization of the standard (cont'd)
  - Normative Appendix A: Operative Temperature and Procedure for Section 5.3
  - Normative Appendix B: Computer Program for Calculation of Predicted Mean Vote (PMV)
  - Normative Appendix C: Procedure for Calculating Comfort Impact of Solar Gain on Occupants
  - Normative Appendix D: Procedure for Evaluating Cooling Effect of Elevated Air Speed Using Standard Effective Temperature (SET)
  - Informative appendices

4. ASHRAE Standard 55

- Purpose of the standard
  - 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
- Scope
  - Addresses the four primary environmental factors (temperature, thermal radiation, humidity and air speed) and two personal factors (activity and clothing) that affect thermal comfort. Applicable for healthy adults at atmospheric pressures in altitudes up to 3,000 m, and for indoor spaces designed for occupancy of at least 15 minutes

4. ASHRAE Standard 55

- Methods of determining thermal comfort:
  - 1. Graphical method (simple but limited in usability)
  - 2. Analytical method (powerful, requires calculations)
  - 3. Elevated air speed (modified graphical or analytical method to account for increased air speed)
  - 4. Adaptive method (applied only to naturally conditioned space)

4. ASHRAE Standard 55

- Comfort zones
  - Defined using isotherms parallel to effective temperature (ET)
  - ASHRAE comfort zones for summer and winter (for typical indoor and seated person)
  - Proposed **comfort zones**
    - Within 5 to 16 mm Hg water vapour pressure
    - Standard effective temperature (SET)
    - For summer, 22.8 $^{o}C \leq SET \leq 26.1\ ^{o}C$
    - For winter, 20.0 $^{o}C \leq SET \leq 23.9\ ^{o}C$

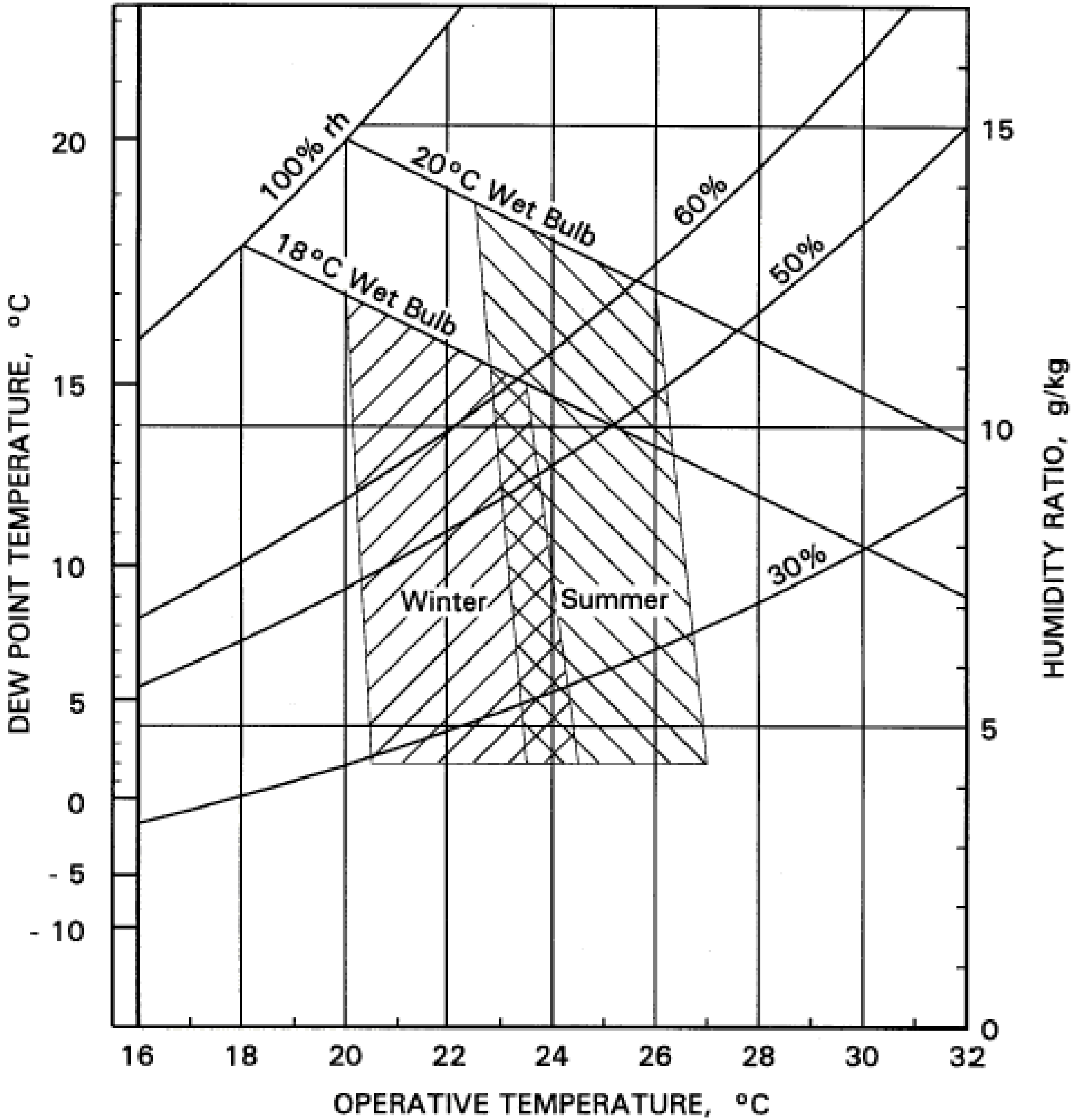
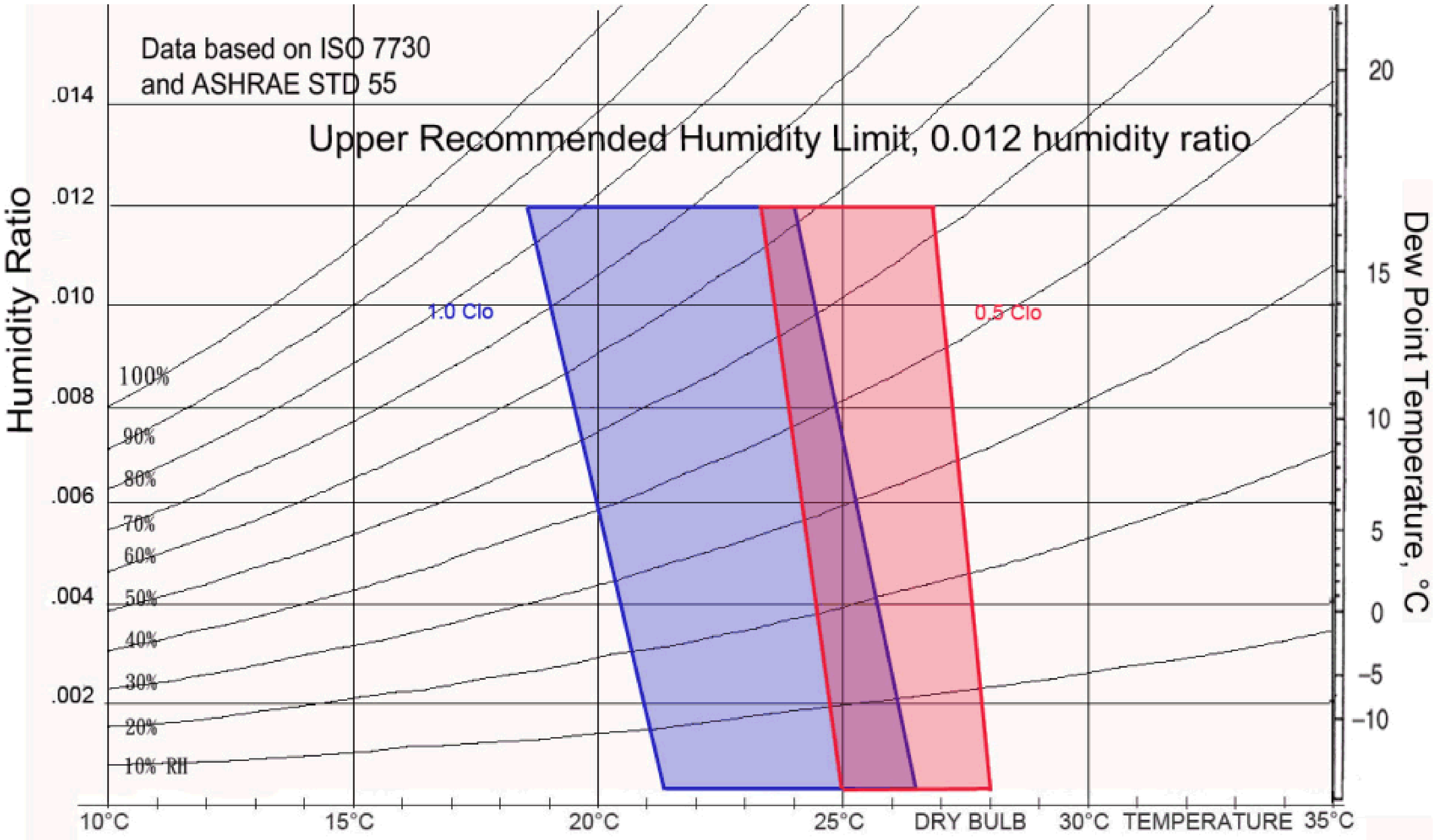


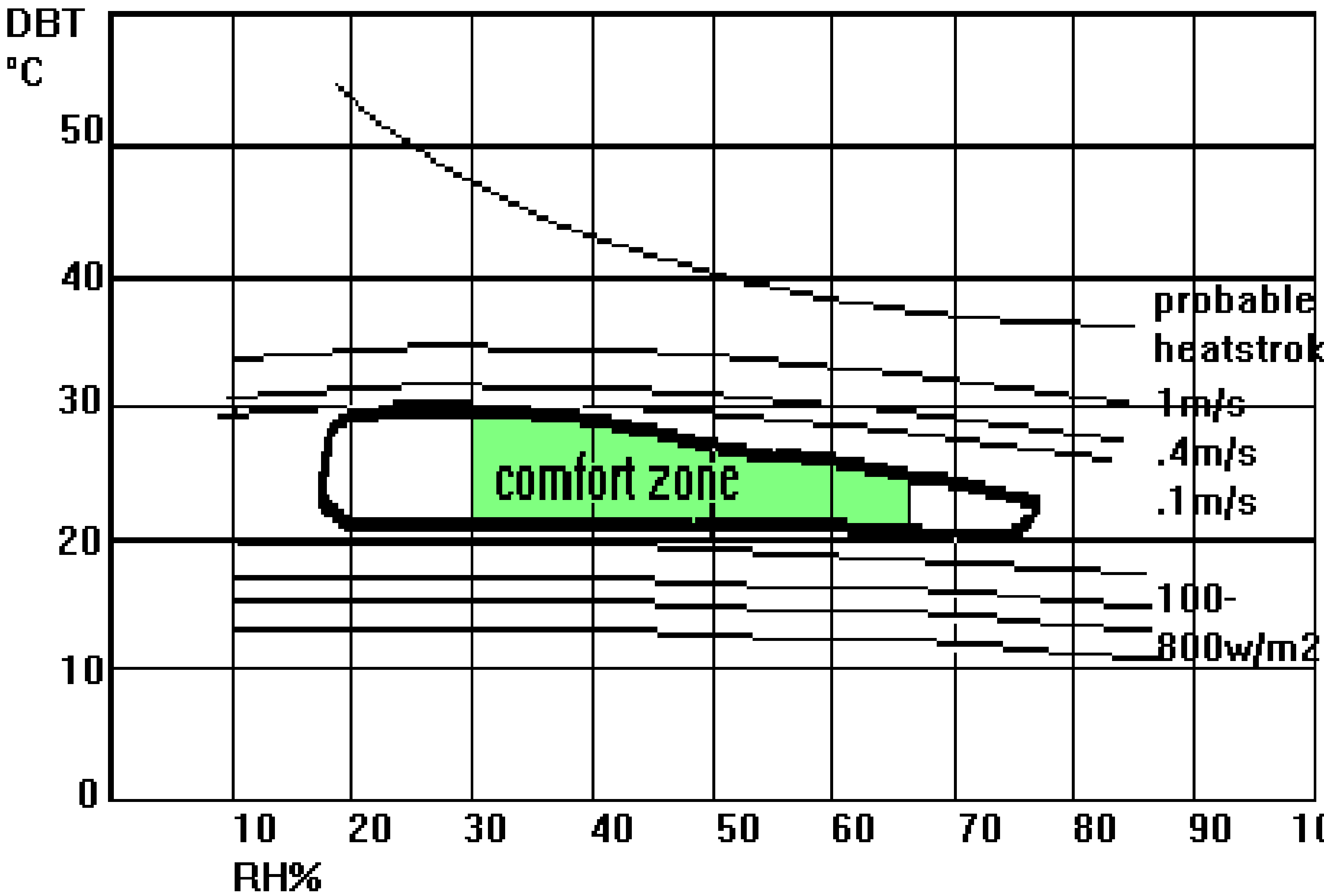
Fig. 5 ASHRAE Summer and Winter Comfort Zones

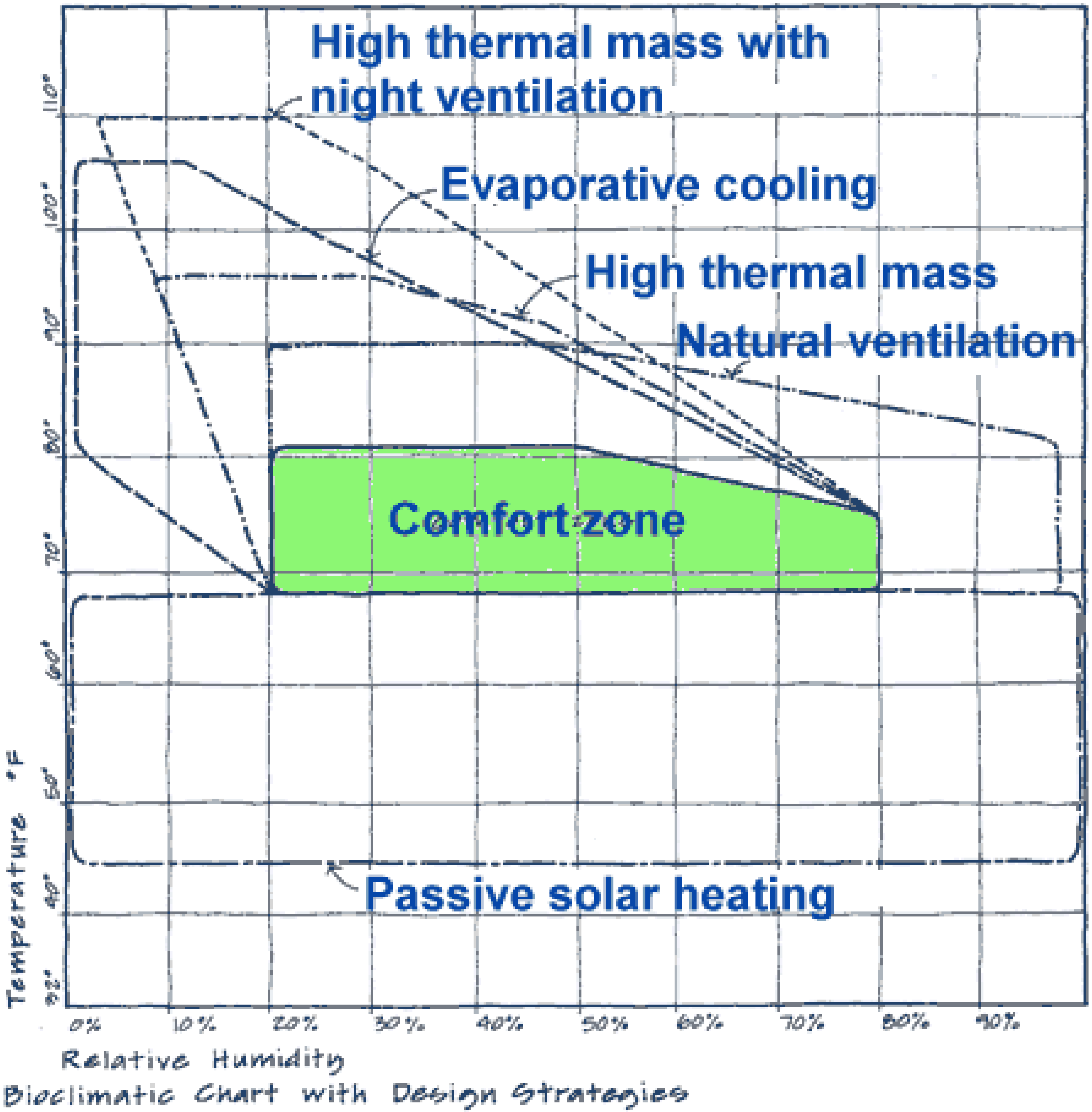
(Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during primarily sedentary activity.)

ASHRAE Comfort Zones
(based on 2004 version of ASHRAE Standard 55)

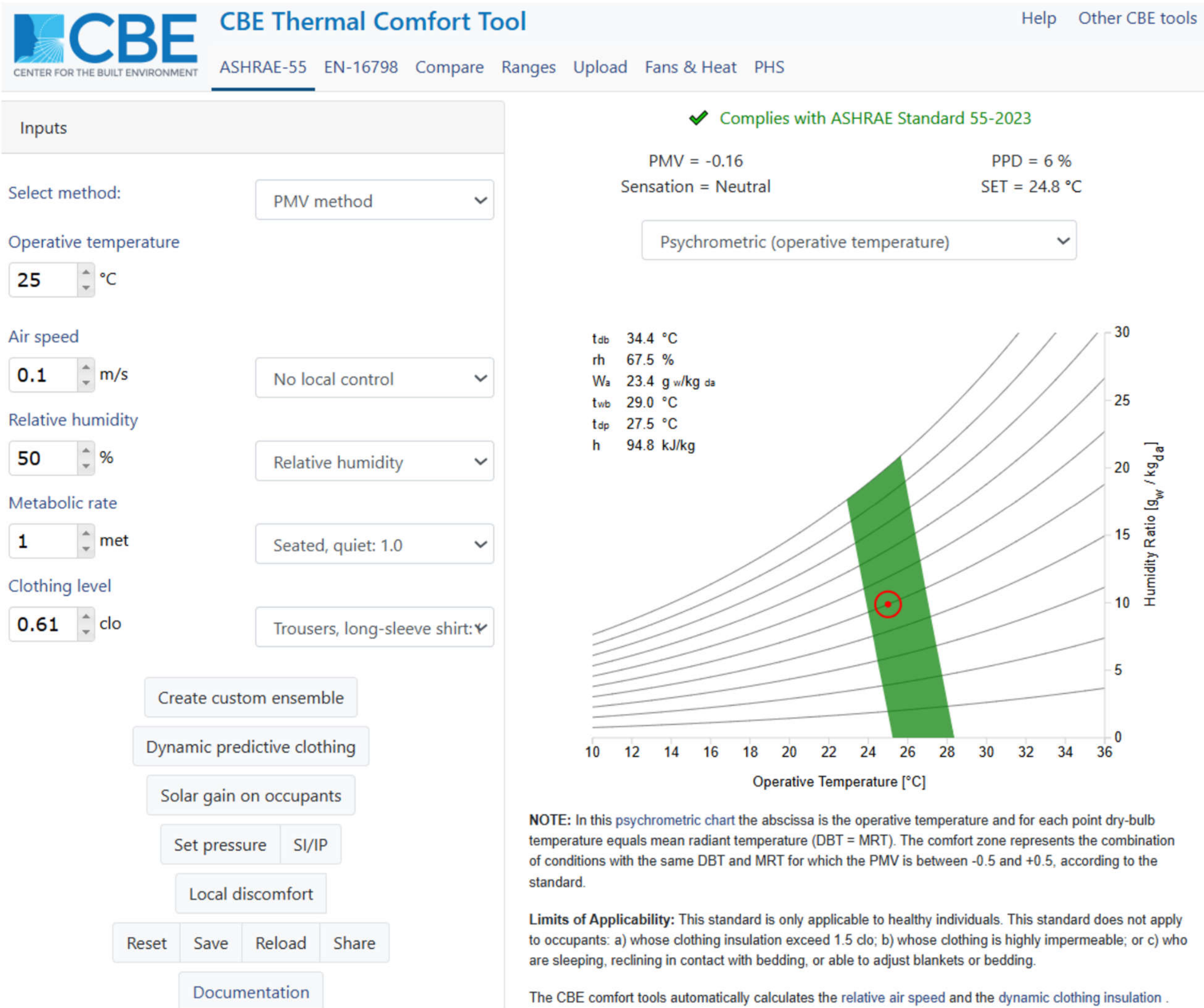


Olgyays bioclimatic chart



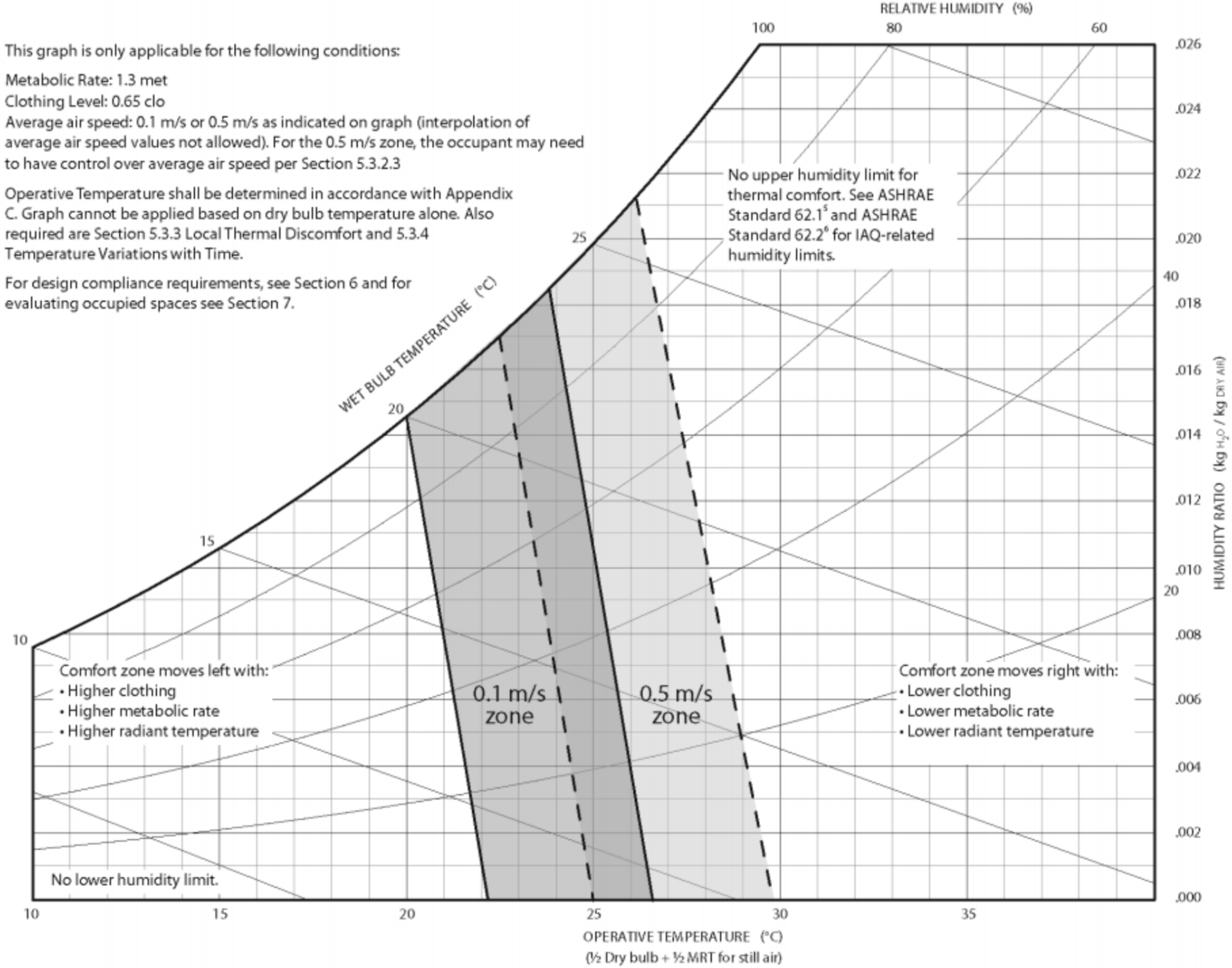

High thermal mass with night ventilation
Evaporative cooling
High thermal mass
Natural ventilation
Comfort zone
Passive solar heating
Temperature °F
32°
40°
50°
60°
70°
80°
90°
100°
110°
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Relative Humidity
Bioclimatic Chart with Design Strategies

Analytical comfort zone method



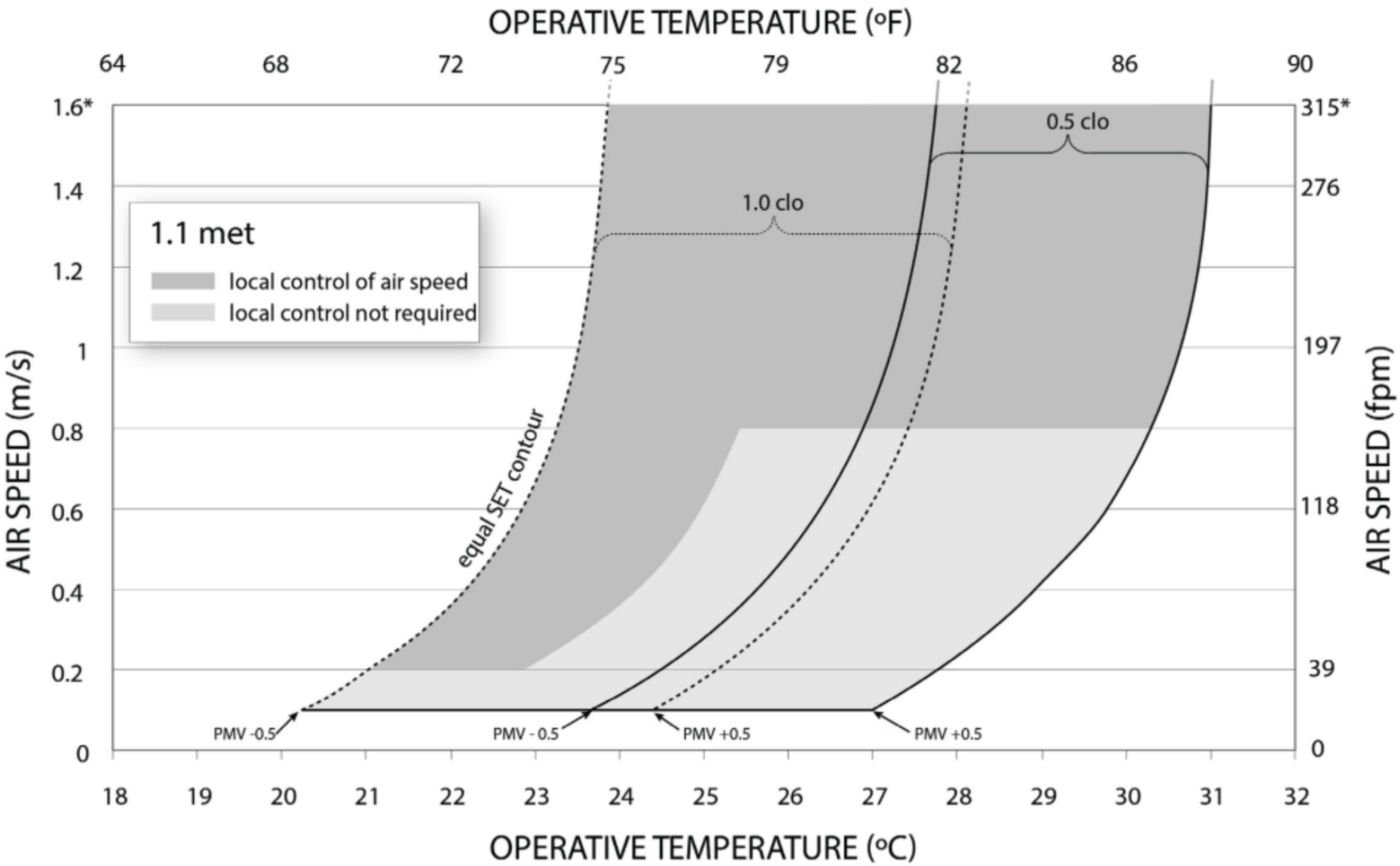
(Source: CBE Thermal Comfort Tool https://comfort.cbe.berkeley.edu/)

Elevated air speed comfort zone example (lightly shaded zone) compare to the still-air comfort zone example (darkly shaded zone)



(Source: ASHRAE Standard 55-2023)

Satisfactory ranges of operative temperature to and average air speed *V*a for 1.0 and 0.5 clo comfort zones at humidity ratio 0.010



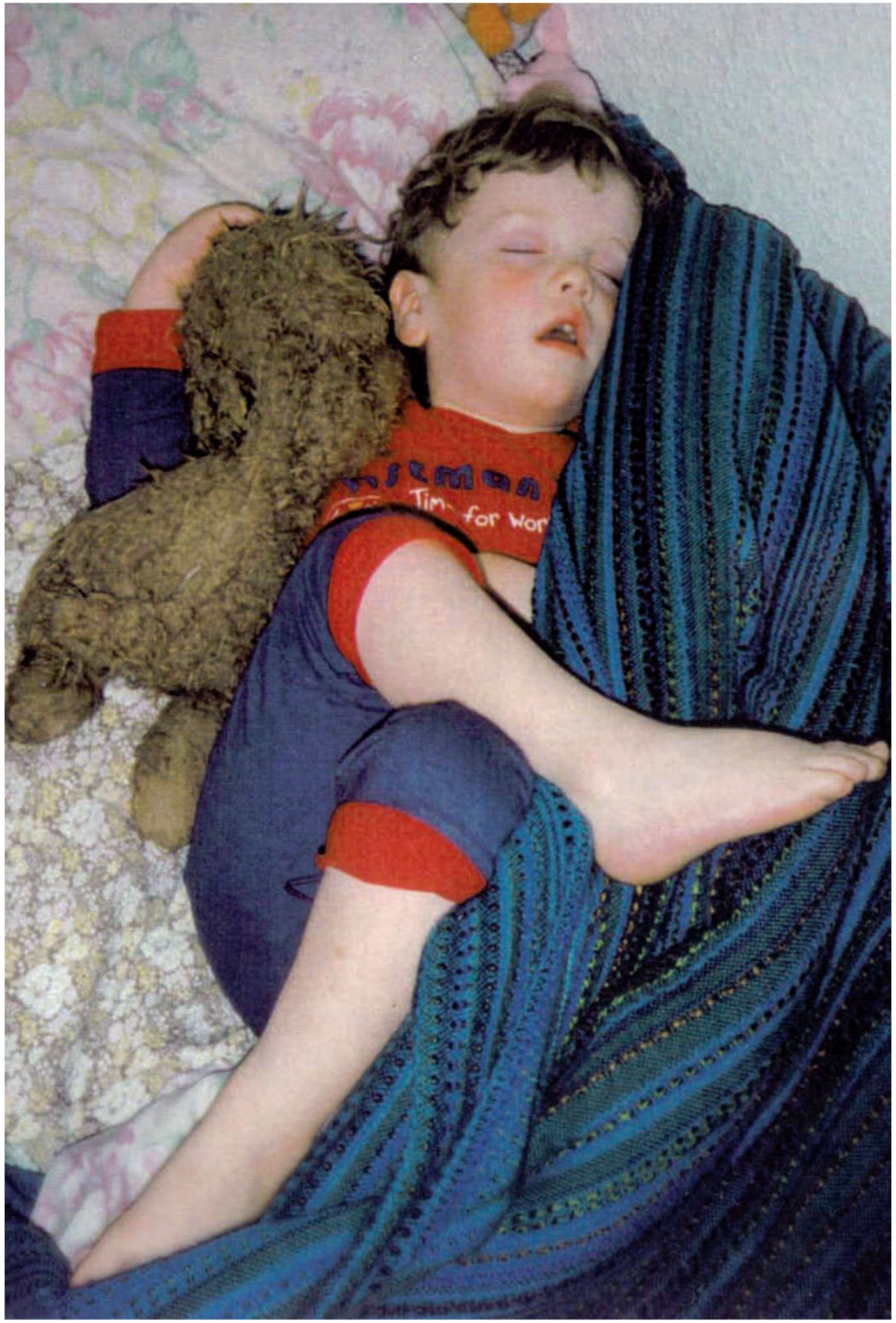
* There is no upper limit to air speed when occupants have local control.

(Source: ASHRAE Standard 55-2023)

4. ASHRAE Standard 55

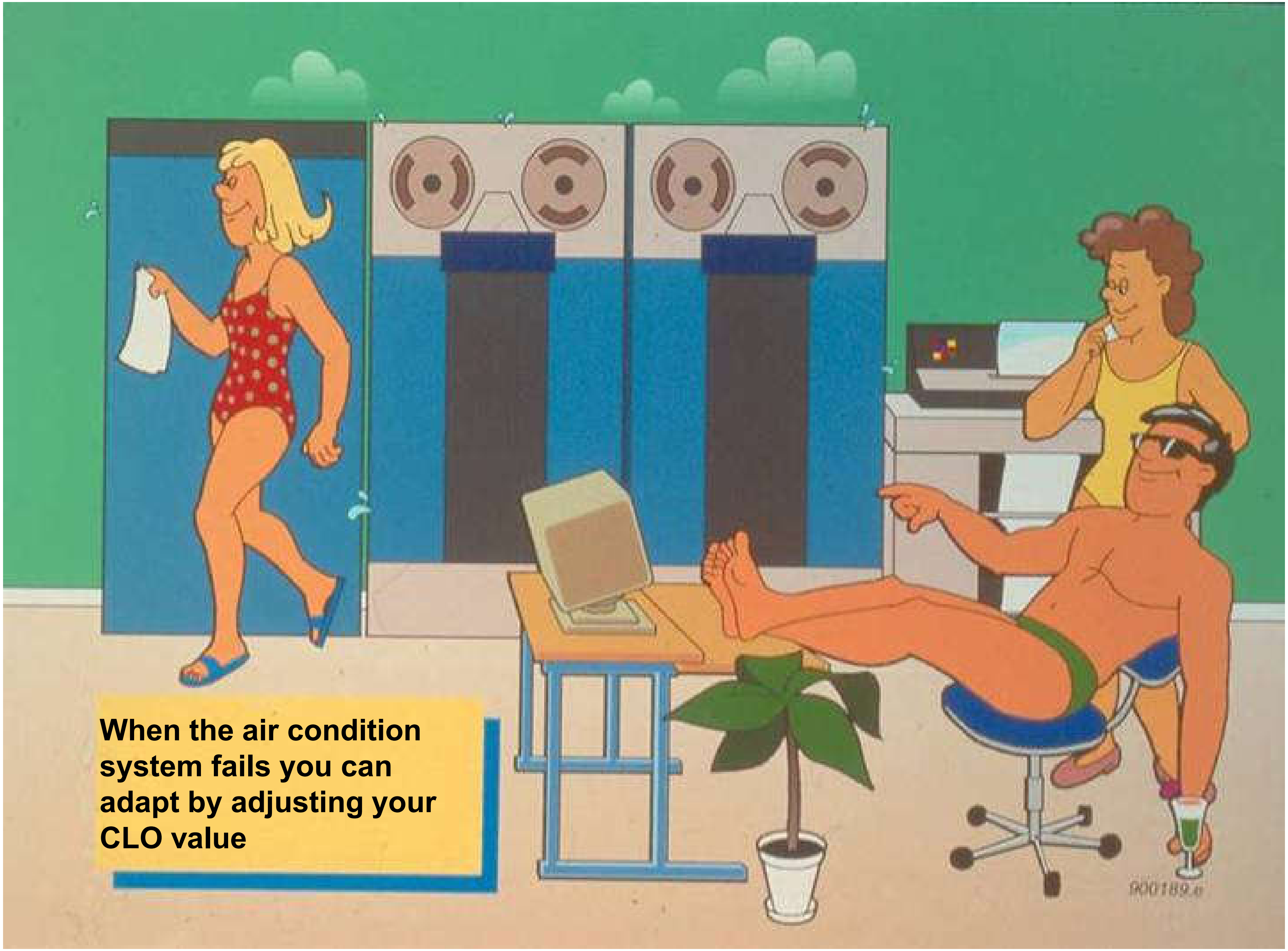
- Adaptive thermal comfort
  - People expect different thermal experiences in summer and winter, and modify behaviour accordingly
  - Comfort temperature can vary with changing outdoor conditions (esp. for natural ventilation)
    - Can reduce the average indoor–outdoor temperature difference, and consequently reduces energy requirements
    - Comfort in intermediate and outdoor spaces

Adaptation need not be a conscious act, and not only for human

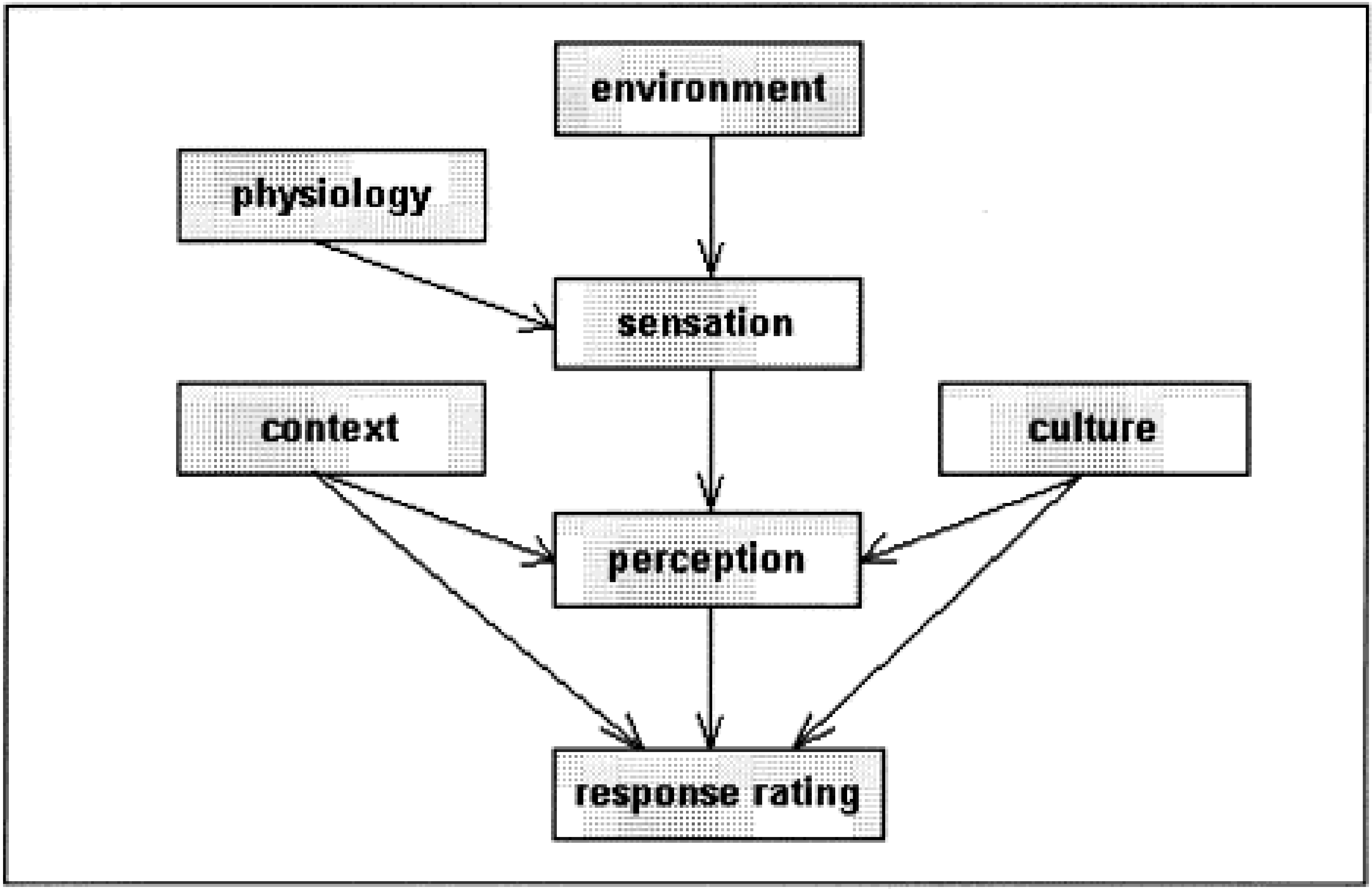


(Source: Nicol, F., Humphreys, M. and Roaf, S., 2012. *Adaptive Thermal Comfort: Principles and Practice*)

Acclimatisation/Adaptation!

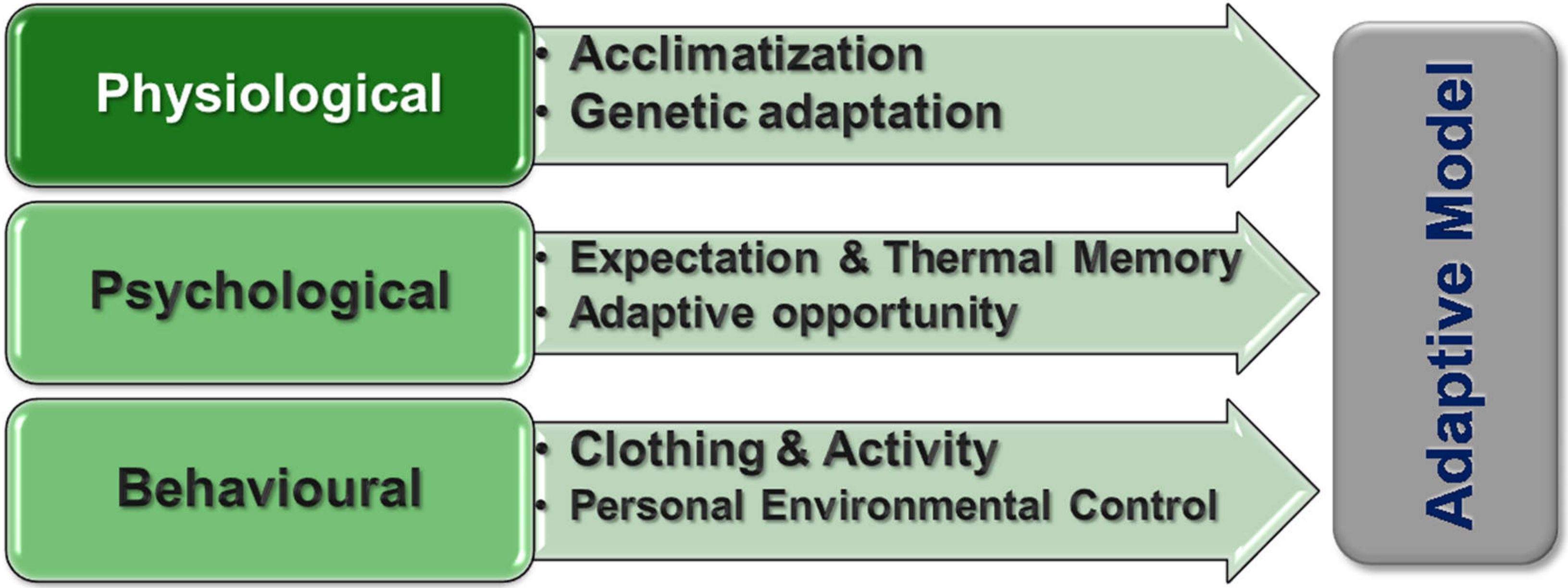


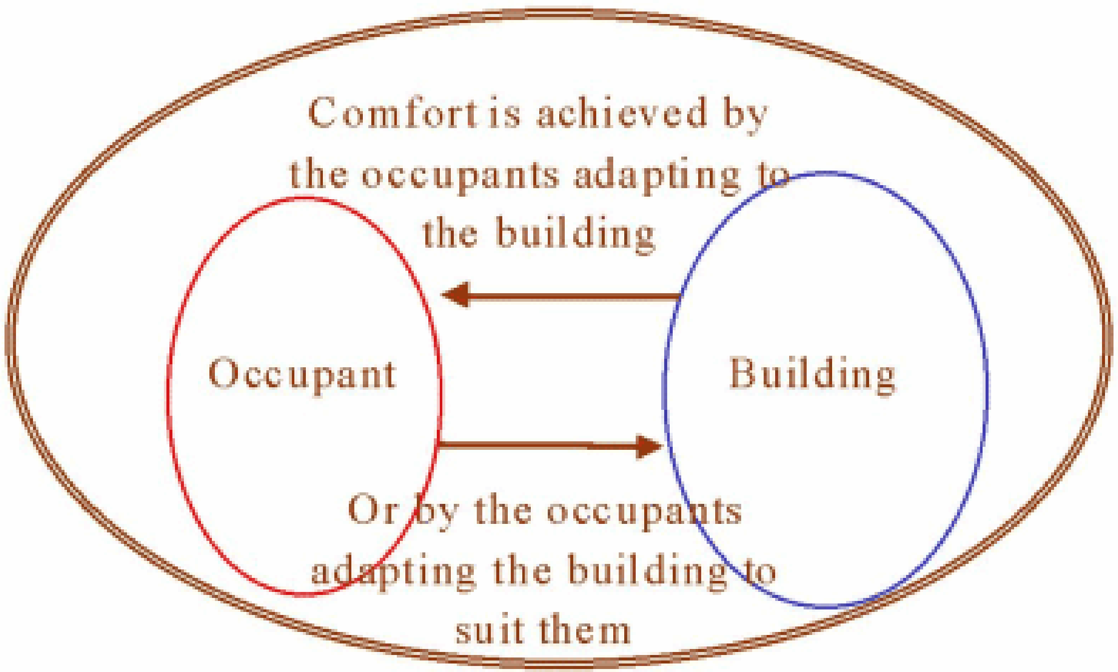
The adaptation model



(Source: Butera, F. M., 1998. Principles of thermal comfort, *Renewable and Sustainable Energy Review*, 2 (1-2): 39-66.)

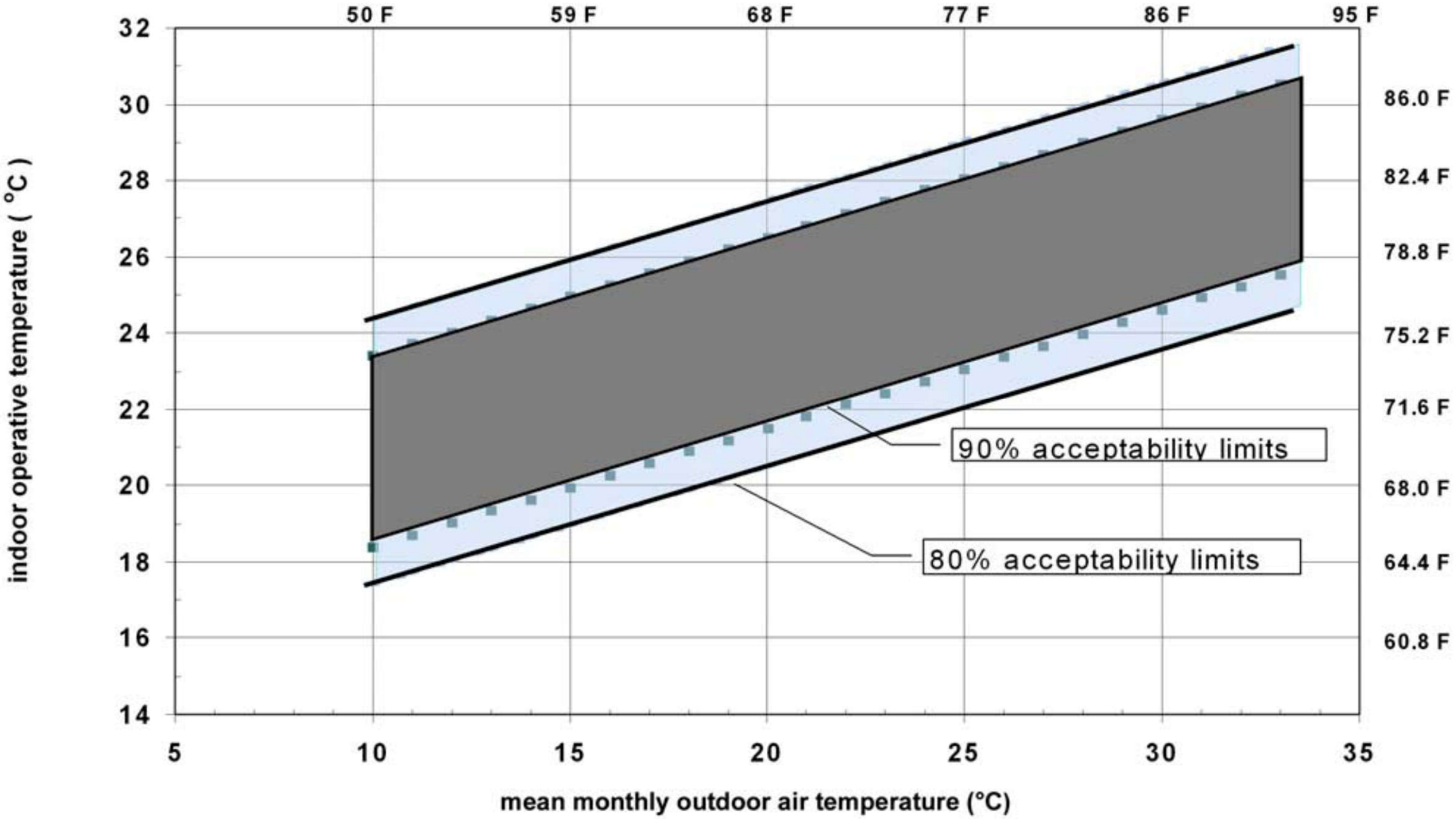
Basic concepts of adaptive thermal comfort





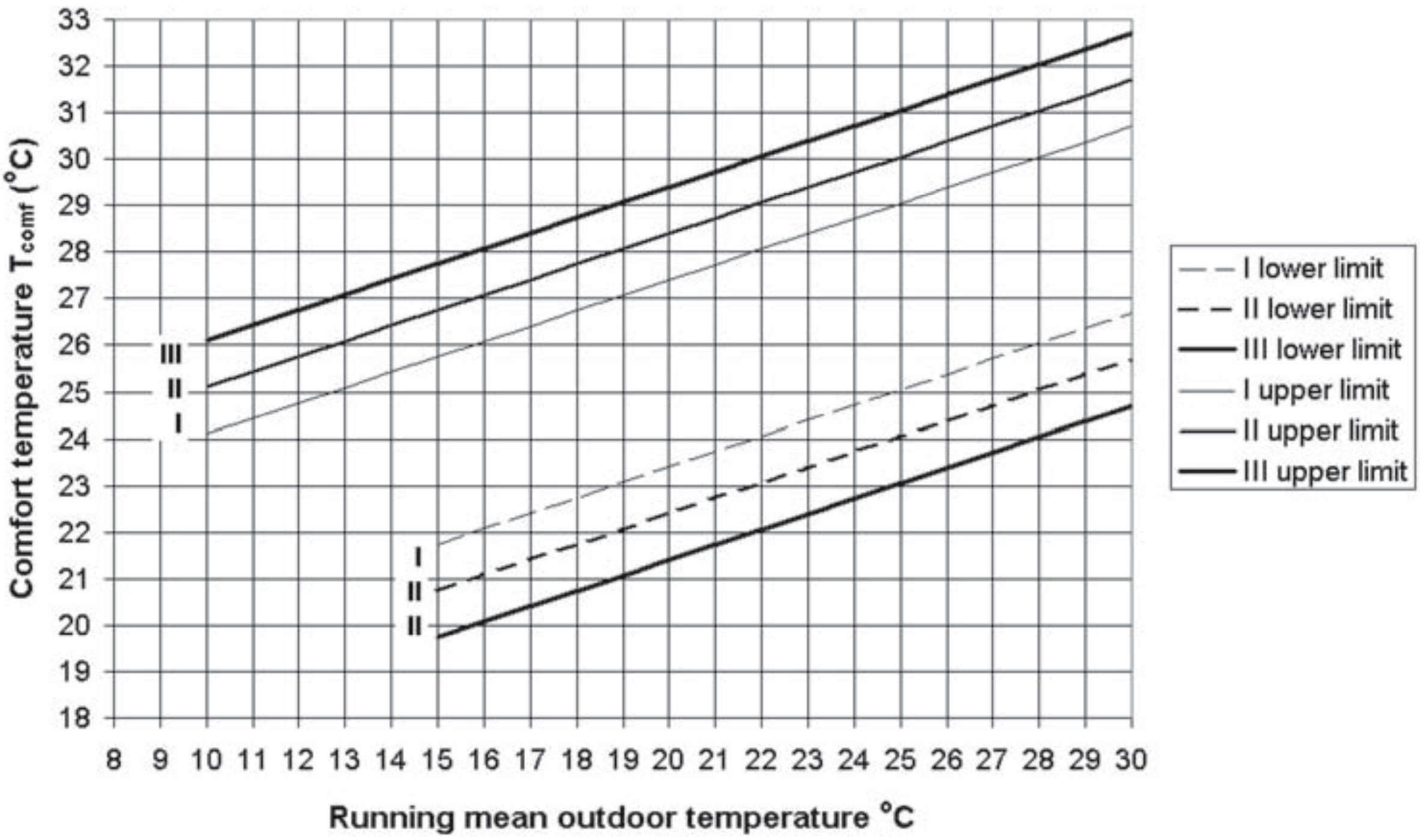
This has to be done within the climatic, social, economic and cultural context of the whole system

Acceptable operative temperature ranges for naturally conditioned spaces



(Source: ASHRAE Standard 55-2010)

Acceptable operative temperature ranges for free-running naturally conditioned spaces (after standard EN15251)



(Source: Nicol, F., Humphreys, M. and Roaf, S., 2012. *Adaptive Thermal Comfort: Principles and Practice*)

Thermal environmental control classification levels

Table 6-1 Thermal Environmental Control Classification Levels

Thermal Environmental Control Classification Level	Control Measure(s) for Environmental Factors Required to Achieve Level	Informative Examples Meeting Thermal Environmental Control Classification Levels
1	Each occupant is provided two or more control measures for their personal environment.	• Private office with a ceiling fan and an occupant adjustable thermostat • Shared office with desktop fans and foot warmers for each occupant
2	Each occupant is provided one control measure for their personal environment.	• Private office with an occupant adjustable thermostat • Shared office with a desktop fan for each occupant
3	The room or thermal zone provides multioccupant control of at least two control measures in their shared environment.	• Shared office with an occupant adjustable thermostat and ceiling fan control
4	The room or thermal zone provides multioccupant control of one control measure in their shared environment.	• Shared office with an occupant adjustable thermostat
5	No occupant control of any environmental factors	• Shared or private office with an unadjustable thermostat or no thermostat

(Source: ASHRAE Standard 55-2023)

5. Thermal Comfort Performance

- To demonstrate compliance the following must be documented, where applicable
  - Method of compliance
  - Design operative temperature and humidity, heating and cooling design outdoor conditions, total indoor loads, and design exceedance hours
  - Assumed values for environmental factors (operative temperature, humidity, and average air speed) and personal factors (clothing insulation and metabolic rate) for heating and cooling design conditions; spaces where personal factors are outside the specified limits should be indicated as not within the standard's scope

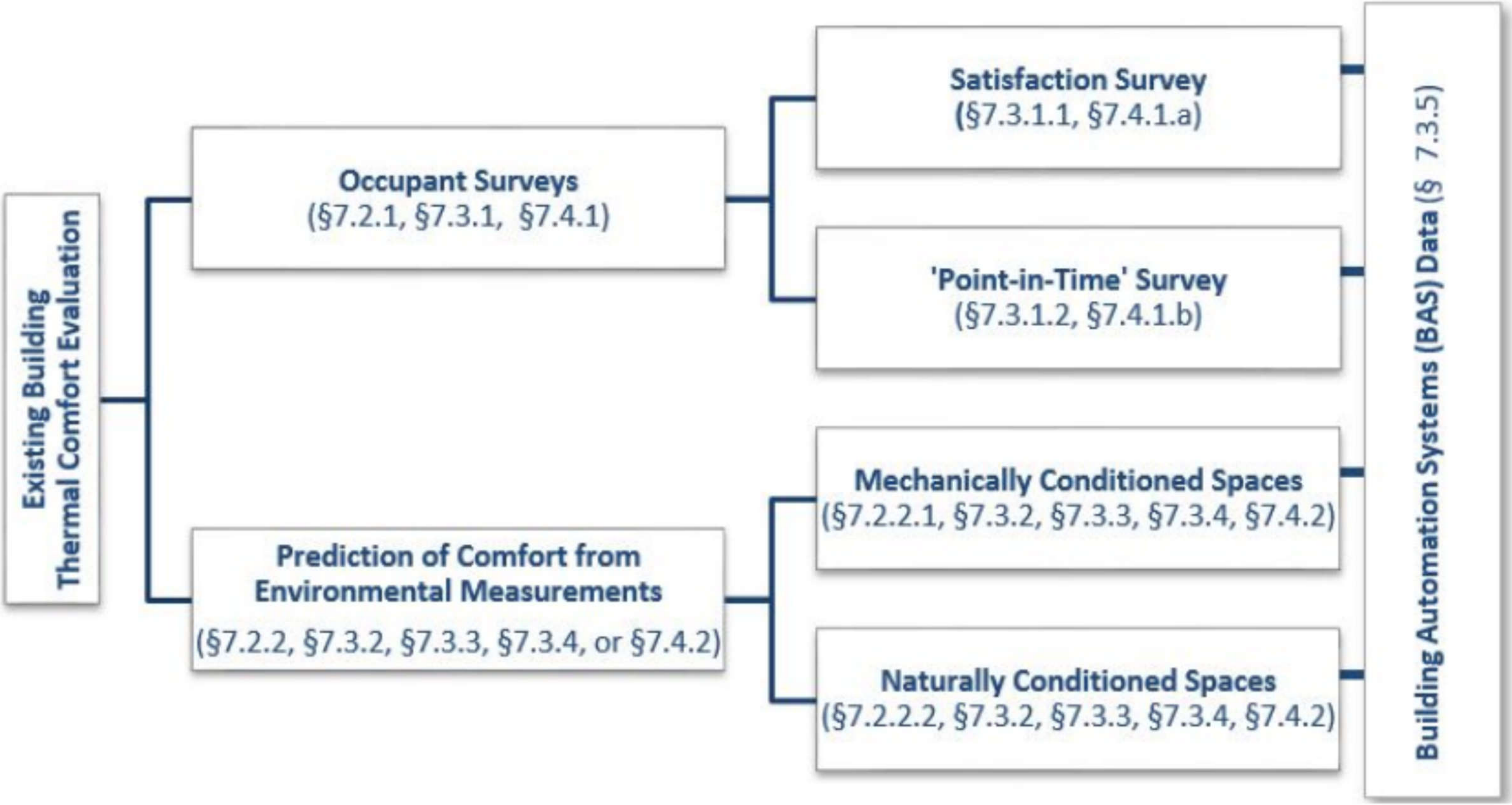
5. Thermal Comfort Performance

- To demonstrate compliance (cont'd)
  - Describe how local thermal discomfort will be addressed, including calculation methods, inputs and results
  - System equipment capacities for each space demonstrating that thermal loads will be met under heating and cooling design conditions
  - Where occupant-controlled elevated air speed is provided, a description of control type
  - Air speed, radiant temperature asymmetry, vertical radiant temperature asymmetry, surface temperatures, and temperature variations in time must be calculated per engineering industry standards

5. Thermal Comfort Performance

- Evaluation of comfort in existing buildings
  - Occupant satisfaction survey
    - The entire occupancy or representative part of the occupancy
    - Thermal sensation scale: cold, cool, slightly cool, neutral, slightly warm, warm, and hot
  - Physical environmental measurements
    - Guideline on the position, time, and equipment accuracy of the physical measurement
    - PMV and SET model shall be used to establish the comfort zone, and the local thermal discomfort shall be evaluated against the limit

Methods of evaluating thermal comfort in existing buildings



(Source: ASHRAE Standard 55-2023)

Thermal environment point-in-time survey

Point-in-Time ("Right Now") Survey

How do you feel right now?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
○	○	○	○	○	○	○
-3	*-2*	*-1*	*0*	*+1*	*+2*	*+3*

How satisfied are you with the thermal environment right now?

Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
○	○	○	○	○	○	○
-3	*-2*	*-1*	*0*	*+1*	*+2*	*+3*

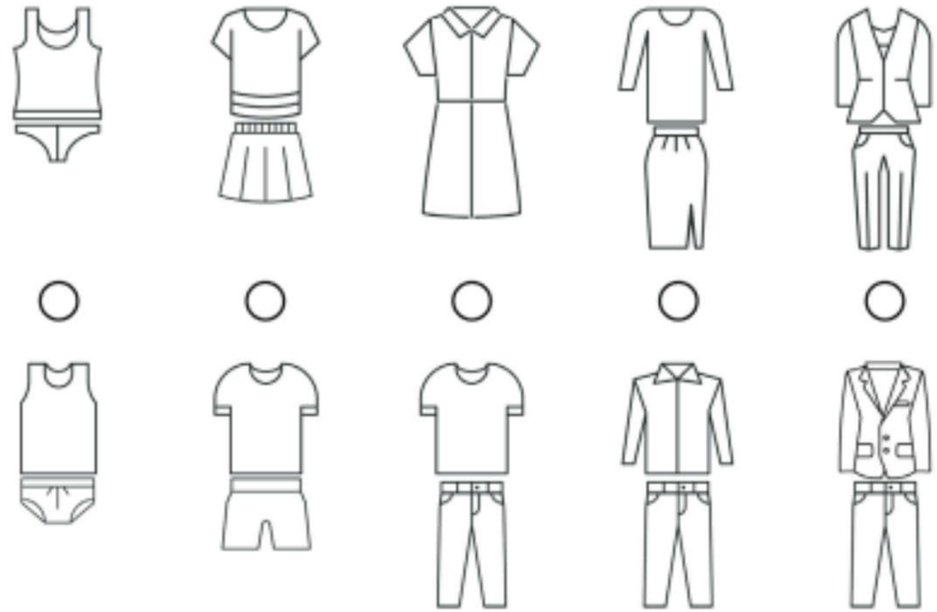
Right now, would you prefer to be...?

Cooler	Without change	Warmer
○	○	○
-1	*0*	*+1*

Right now, would you prefer...?

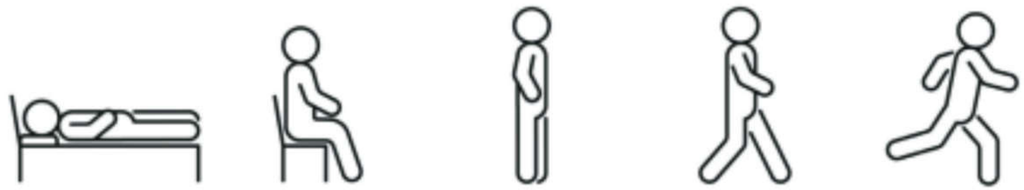
Less air movement	No change	More air movement
○	○	○
-1	*0*	*+1*

Which ensemble best matches what you are wearing right now?



0.2 clo	*0.4 clo*	*0.5 clo*	*0.6 clo*	*1.0 clo*

What is your activity level right now?



○	○	○	○	○
0.8 met	*1.1 met*	*1.2 met*	*1.7 met*	*3.8 met*

(Source: ASHRAE Standard 55-2023)

Instrument measurement range and accuracy

Quantity	Measurement Range	Accuracy
Air temperature	10°C to 40°C (50°F to 104°F)	±0.2°C (0.4°F)
Mean radiant temperature	10°C to 40°C (50°F to 104°F)	±1°C (2°F)
Plane radiant temperature	0°C to 50°C (32°F to 122°F)	±0.5°C (1°F)
Surface temperature	0°C to 50°C (32°F to 122°F)	±1°C (2°F)
Humidity, relative	25% to 95% rh	±5% rh
Air speed	0.05 to 2 m/s (10 to 400 fpm)	±0.05 m/s (±10 fpm)
Directional radiation	–35 W/m^2 to +35 W/m^2 (–11 Btu/h·ft^2 to +11 Btu/h·ft^2)	±5 W/m^2 (±1.6 Btu/h·ft^2)

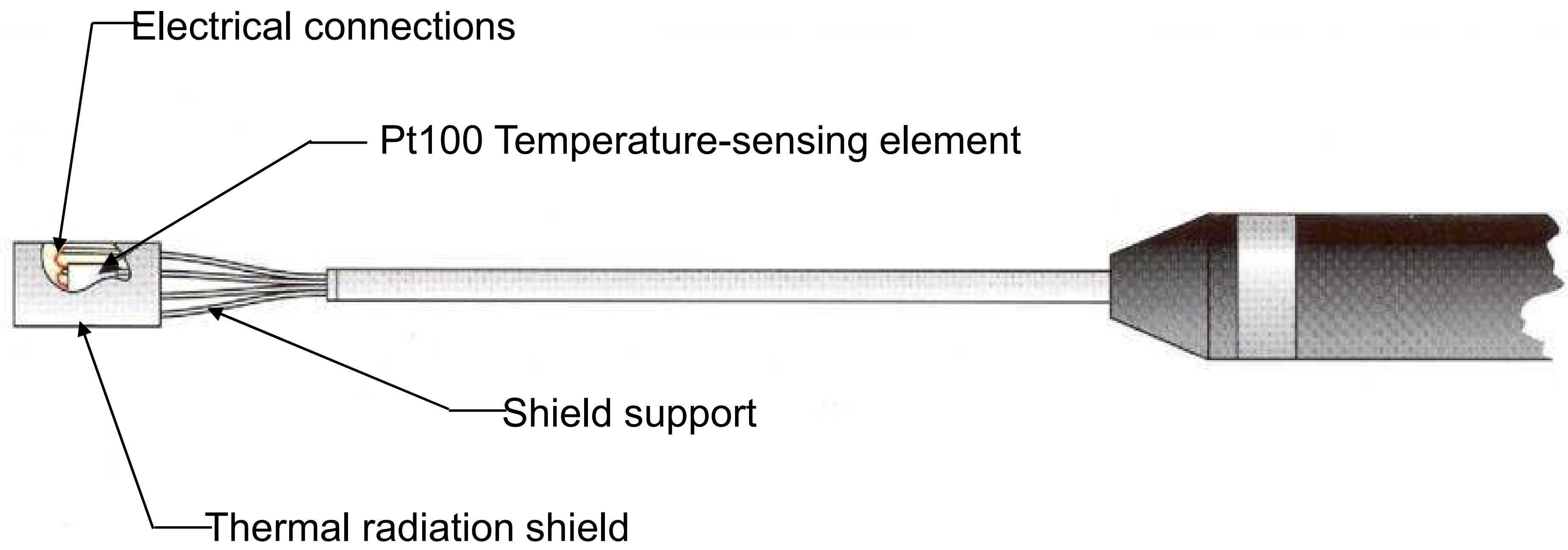
(Source: ASHRAE Standard 55-2023)

Collection of Thermal Comfort Data

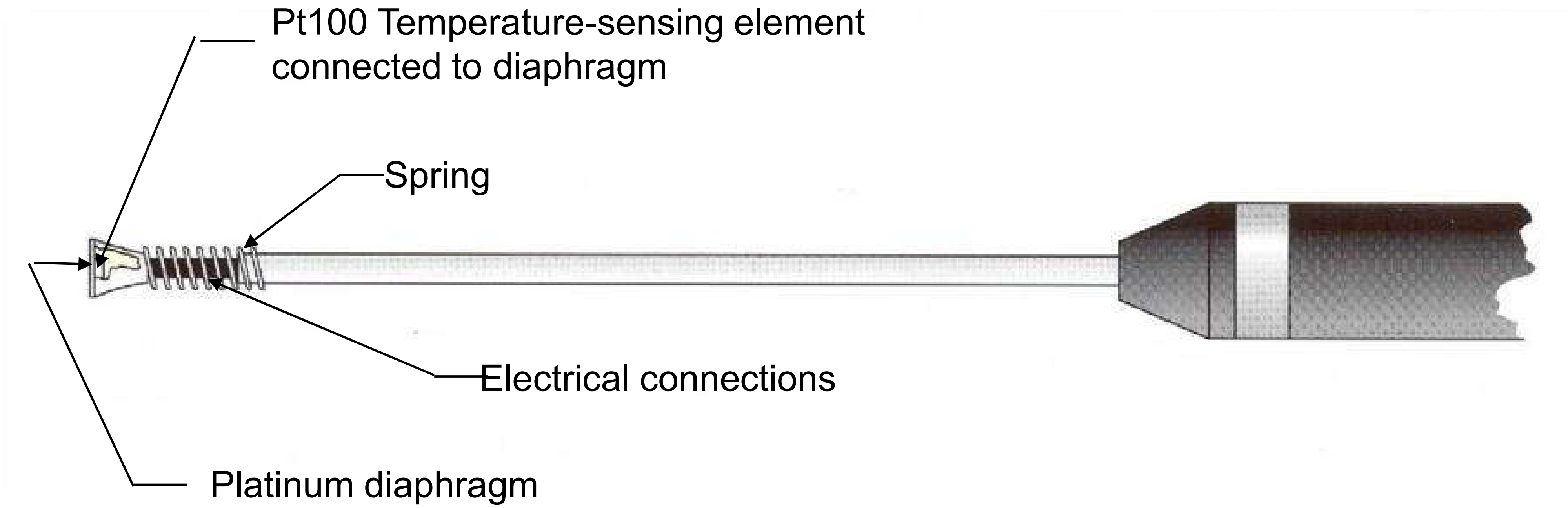
Transducers

- Operative Temperature
- Air Velocity
- Radiant Temperature Asymmetry
- Air Temperature
- Humidity
- Surface Temperature
- WBGT
- Dry Heat Loss

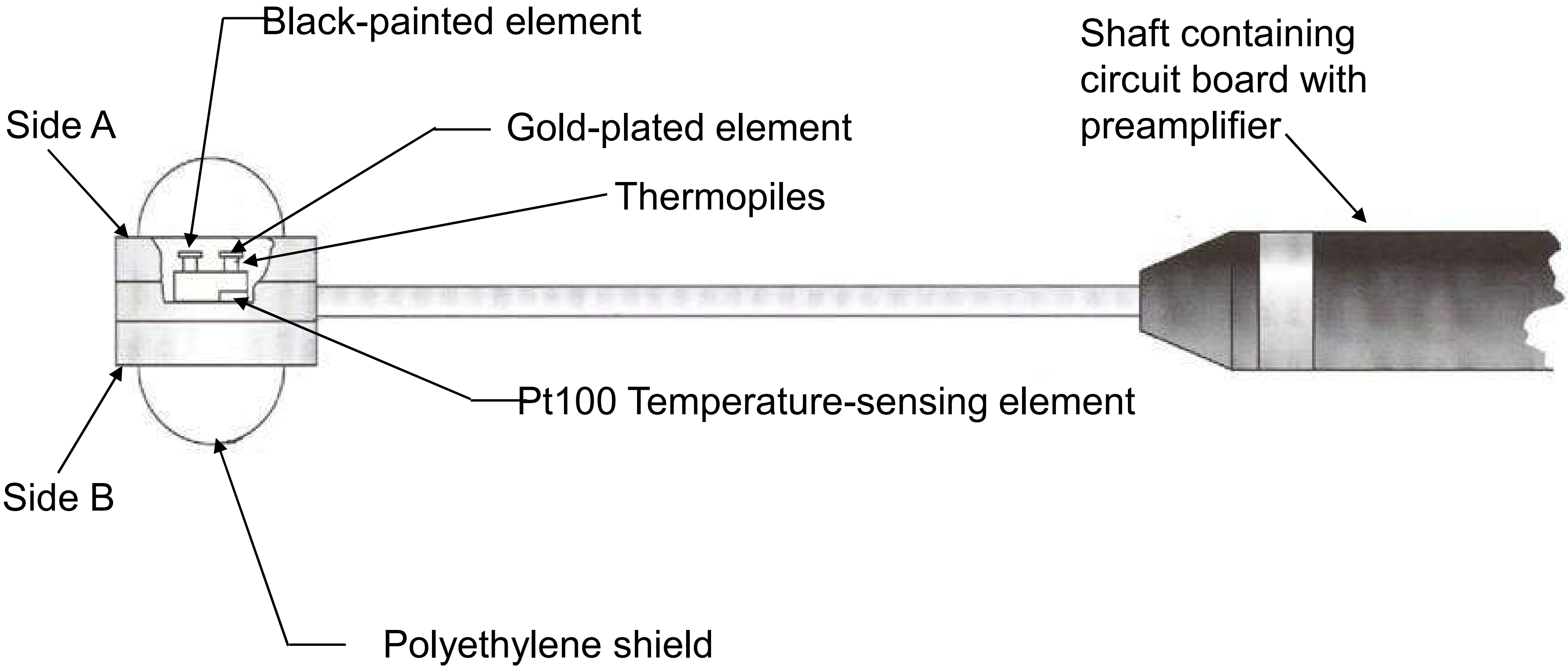
Air Temperature Transducer



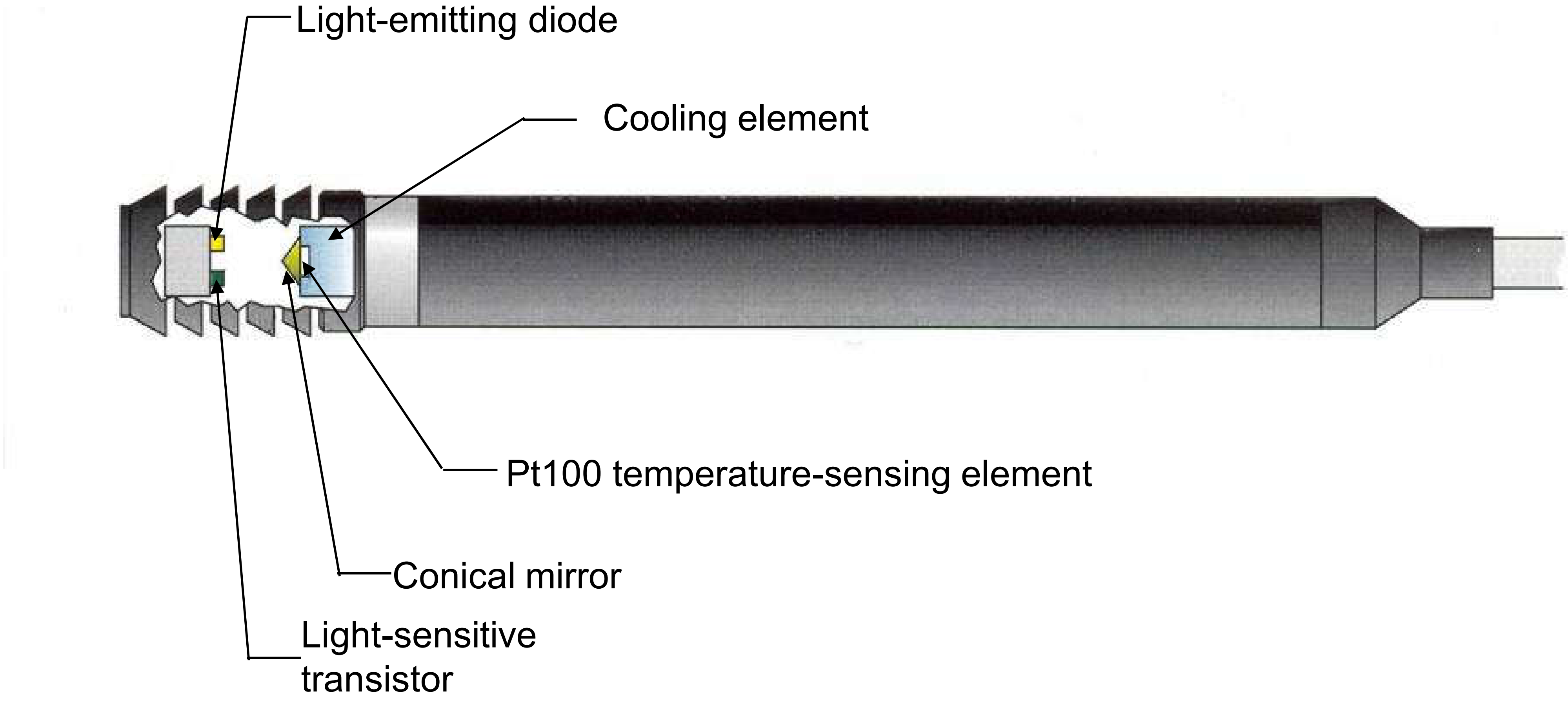
Surface Temperature Transducer



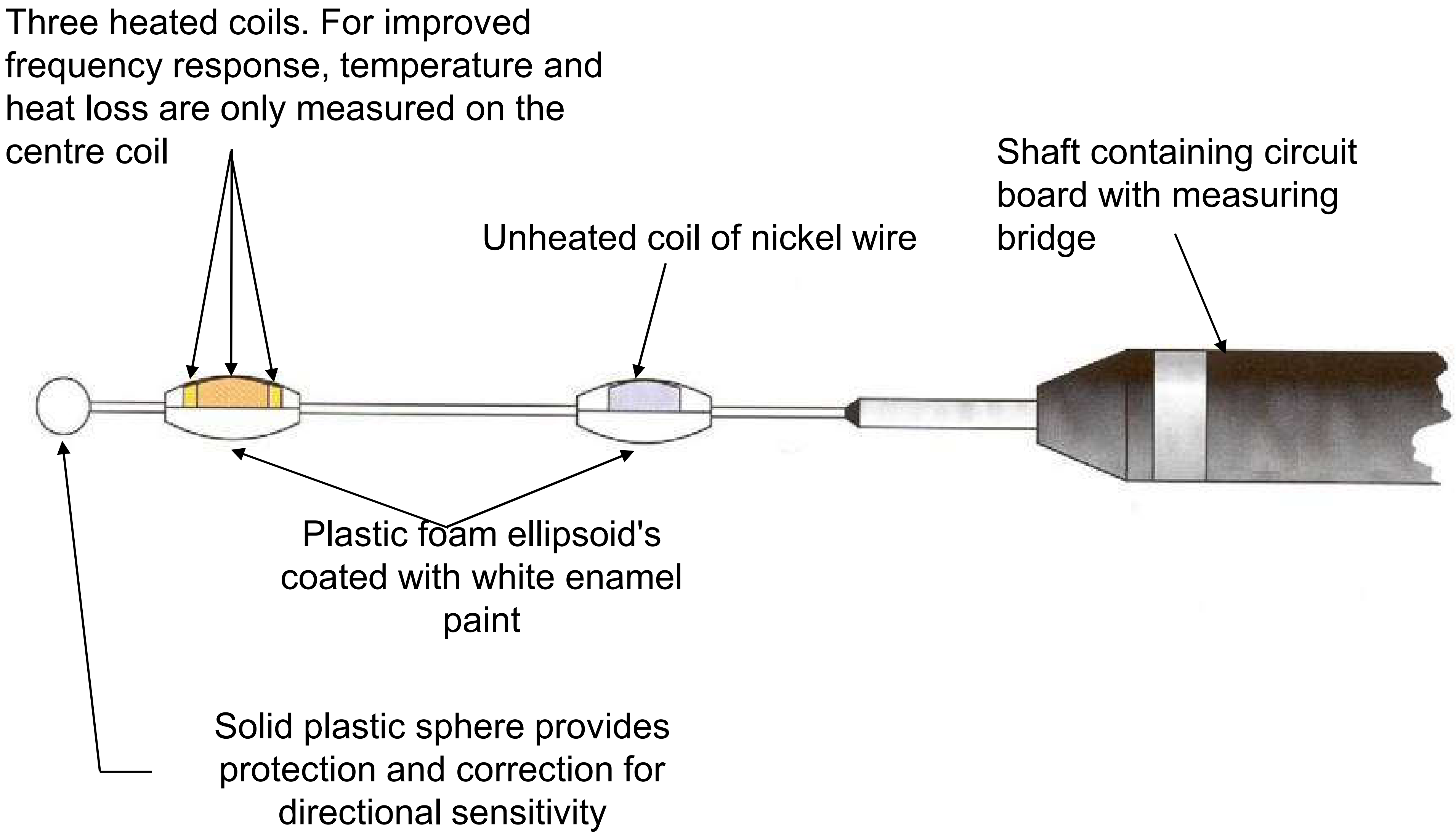
Radiant Temperature Asymmetry Transducer



Humidity Transducer



Air Velocity Transducer



An Example

Comfort data logger with comfort transducer:

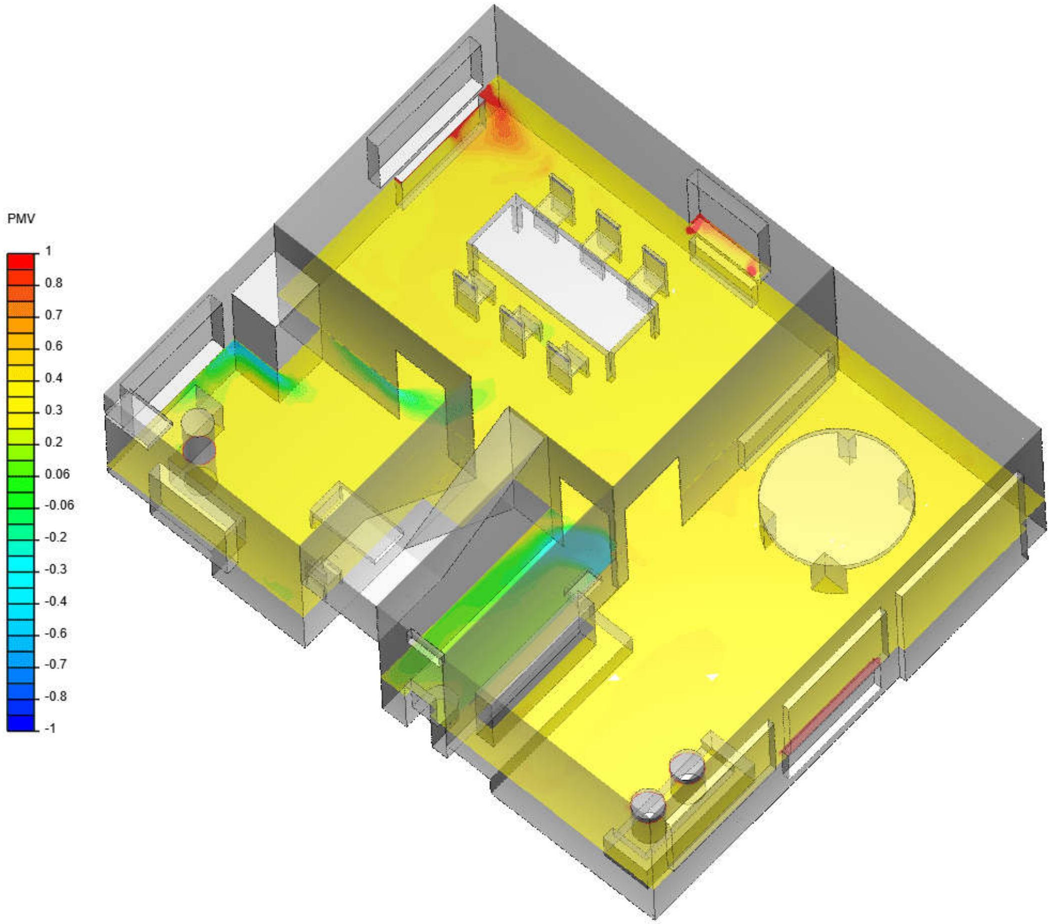
• Holds 6 Comfort Transducers.

• The Mannequin is shaped as a human body.

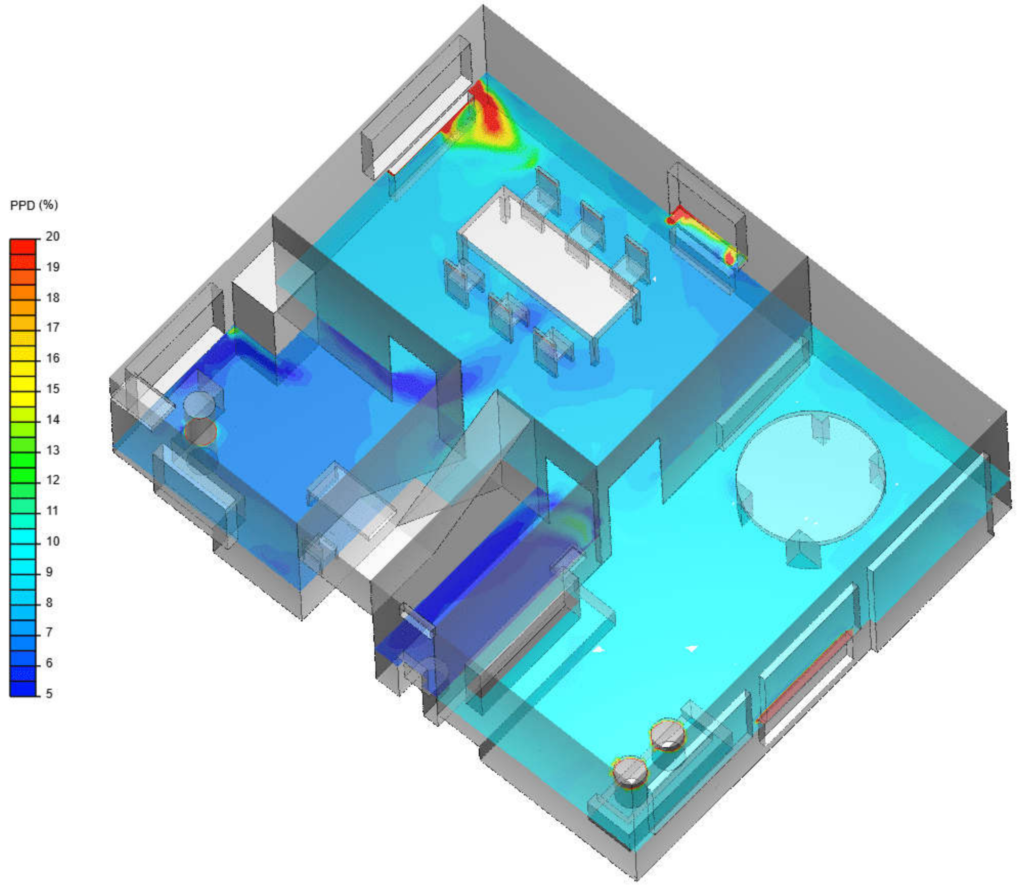
•Cut’s in body parts allows air movement and radiation to influence measurements.

Simulation of thermal comfort parameters: predicted mean vote (PMV) and predicted percentage dissatisfied (PPD)

(a) Predicted mean vote (PMV)



(b) Predicted percentage dissatisfied (PPD)



(Source: What Is ASHRAE 55? Basics of Thermal Comfort https://www.simscale.com/blog/what-is-ashrae-55-thermal-comfort/)

Further Reading

- ASHRAE, 2023. *ASHRAE Standard 55-2023: Thermal Environmental Conditions for Human Occupancy*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.
- Butera, F. M., 1998. Principles of thermal comfort, *Renewable and Sustainable Energy Review*, 2 (1-2): 39-66.
- Fanger, P. O.,1970. *Thermal Comfort: Analysis and Applications in Environmental Engineering*, McGraw-Hill, New York.

E-learning & Web Links

- ASHRAE, 1997. *Thermal Comfort Tool* [computer program] [AV 697.9315 T41]
- Thermal Comfort Tool for ASHRAE-55 (UC Berkeley) https://comfort.cbe.berkeley.edu/
- Thermal comfort -- Wikipedia http://en.wikipedia.org/wiki/Thermal_comfort
- Thermal comfort in buildings https://www.designingbuildings.co.uk/wiki/Thermal_comfort_in_buildings

THANK YOU 謝謝 !!