Comprehensive Certificate Course on Implementation of ASHRAE Standards for LEED Assessment

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Design considerations on thermal comfort (ASHRAE Standard 55)

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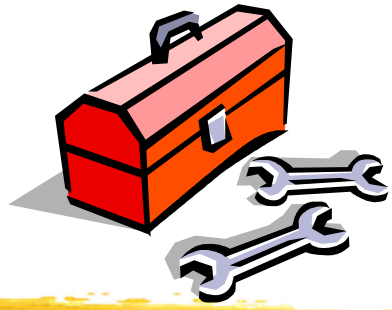
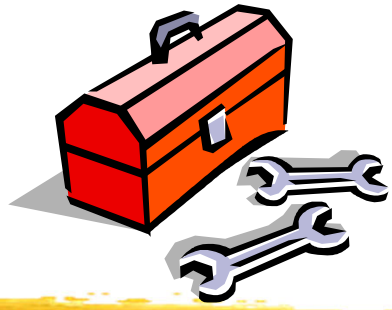
Introduction



- 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

Introduction

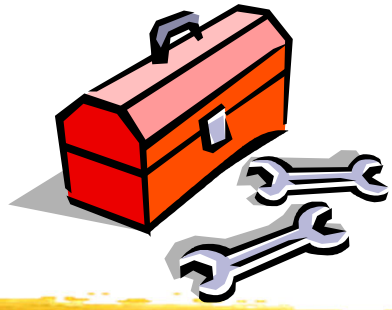


- LEED Green Building Rating System
  - **L**eadership in **E**nergy & **E**nvironmental **D**esign
    - By US Green Building Council
  - Current LEED systems:
    - New construction (LEED-NC) or Building design and construction (BD+C)
    - Existing buildings operations & maintenance (LEED-EBOM) (O+M)
    - Commercial interiors (LEED-CI)
    - Core and shell (LEED-CS)
    - Homes, Schools, Healthcare, Retail
    - Neighborhood development (LEED-ND)

LEED Green Building Rating

(Source: USGBC http://www.usgbc.org/leed)

Introduction

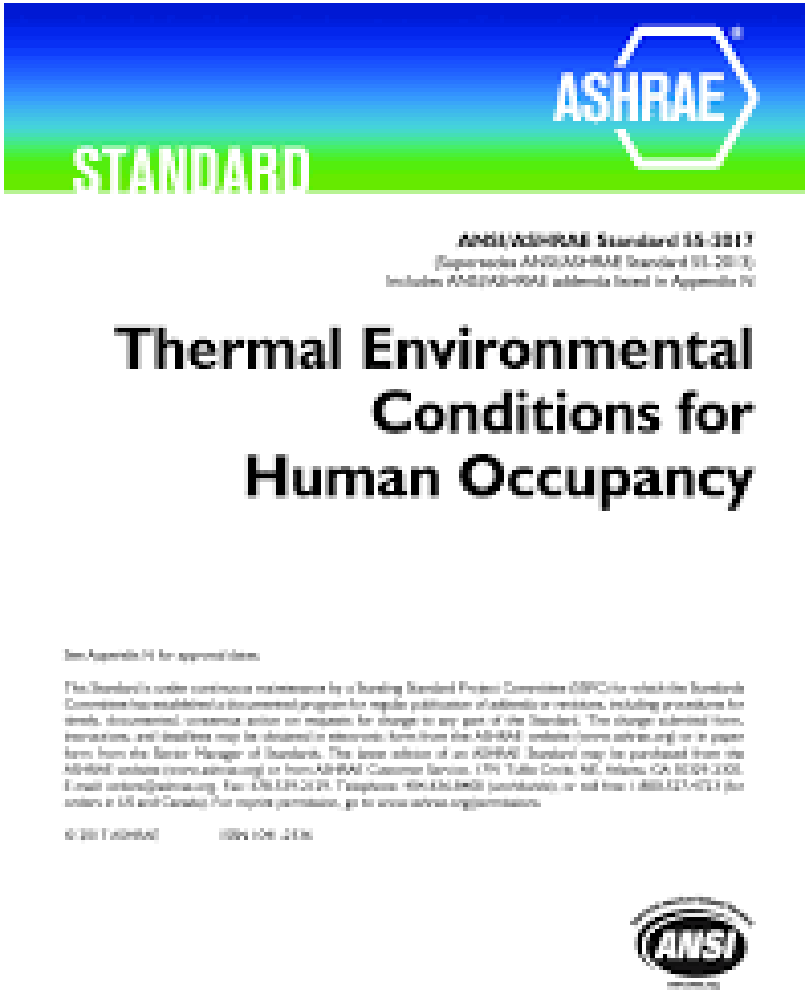


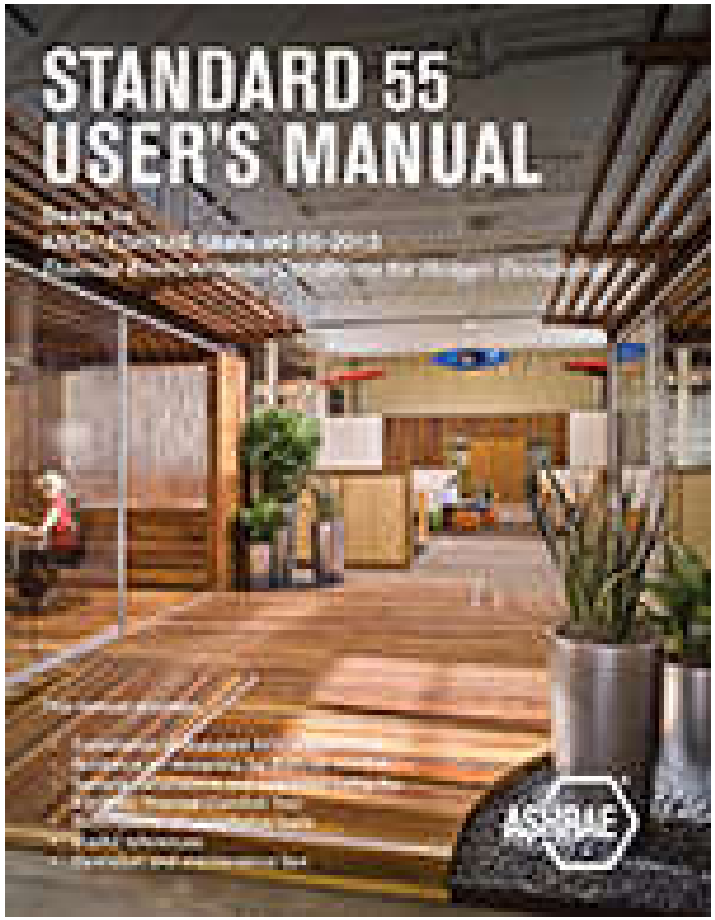
- LEED v4 (launched in 2014)*
  - Location & Transportation (LT)
  - Sustainable Site (SS)
  - Water Efficiency (WE)
  - Energy and Atmosphere (EA)
  - Materials and Resources (MR)
  - Indoor Environmental Quality (EQ)
  - Innovation (IN)
  - Regional Priority (RP)

(* See also http://new.usgbc.org/leed/v4)

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





(Source: www.ashrae.org)

ASHRAE Standard 55

- It is a standard that provides minimum requirements for acceptable thermal indoor environments
  - Establishes the ranges of indoor environmental conditions that are acceptable to achieve thermal comfort for occupants
  - It was first published in 1966, and since 2004 has been updated periodically

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

ASHRAE Standard 55

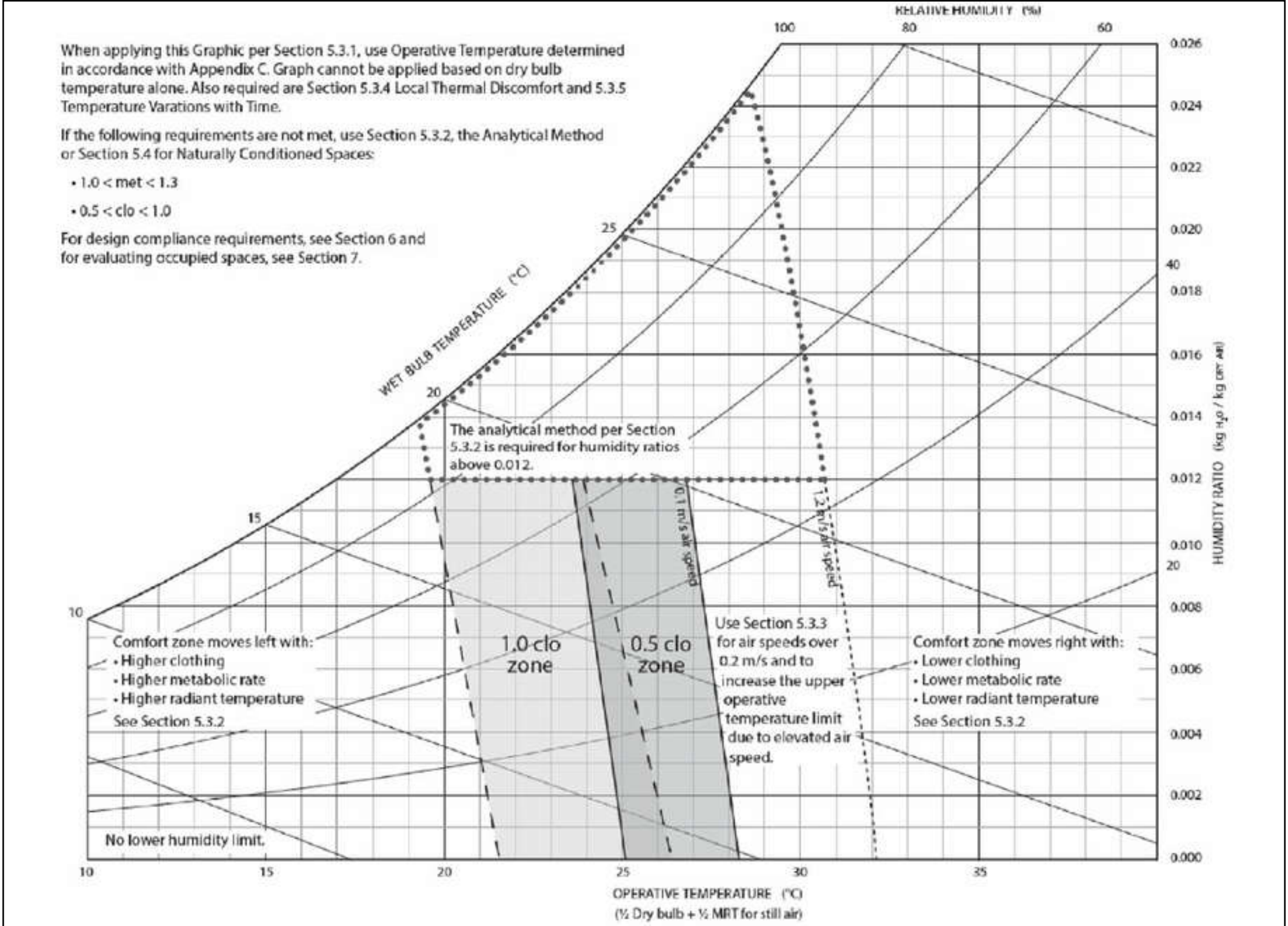
- Organization of the standard (cont'd)
  - Normative Appendix A: Methods for determining operative temperature
  - Normative Appendix B: Computer program for calculation of PMV/PPD
  - 11 informative appendices (these are not part of the standard, but provide additional information about terms and methods described within the standard, as well as a bibliography)

ASHRAE Standard 55

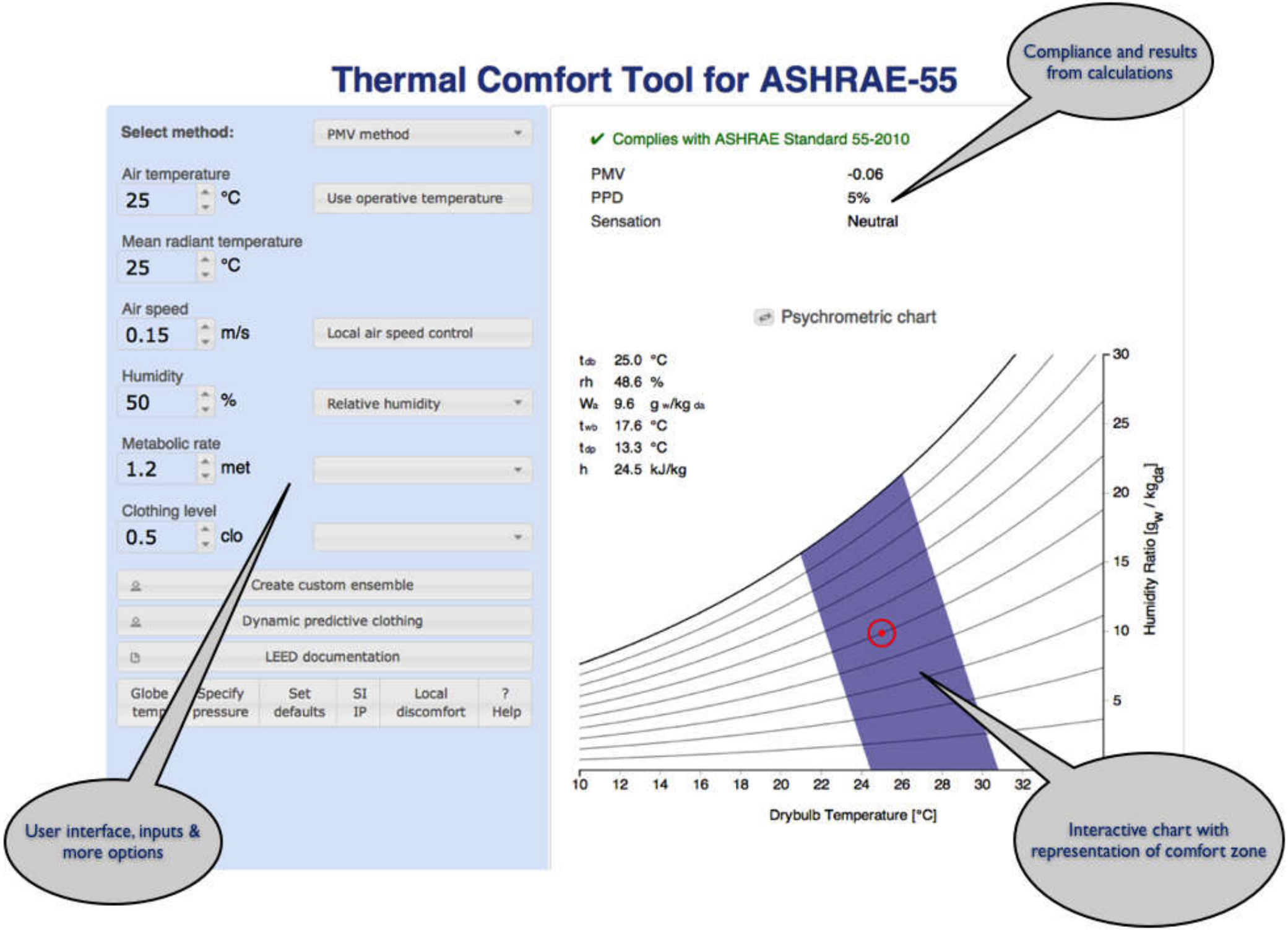
- Purpose of the standard
  - To specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space
- Scope
  - Addresses the four primary environmental factors (temperature, thermal radiation, humidity, and air speed) and two personal factors (activity and clothing) that affect thermal comfort. It is applicable for healthy adults at atmospheric pressures in altitudes up to (or equivalent to) 3,000 m, and for indoor spaces designed for occupancy of at least 15 minutes

ASHRAE Standard 55

- Methods to evaluate thermal comfort:
  - 1. Graphic comfort zone method for simple situations
  - 2. Analytical comfort zone method for more general cases
  - 3. A method that uses elevated air speed to provide comfort
- A separate method for determining acceptable thermal conditions in occupant-controlled naturally conditioned spaces

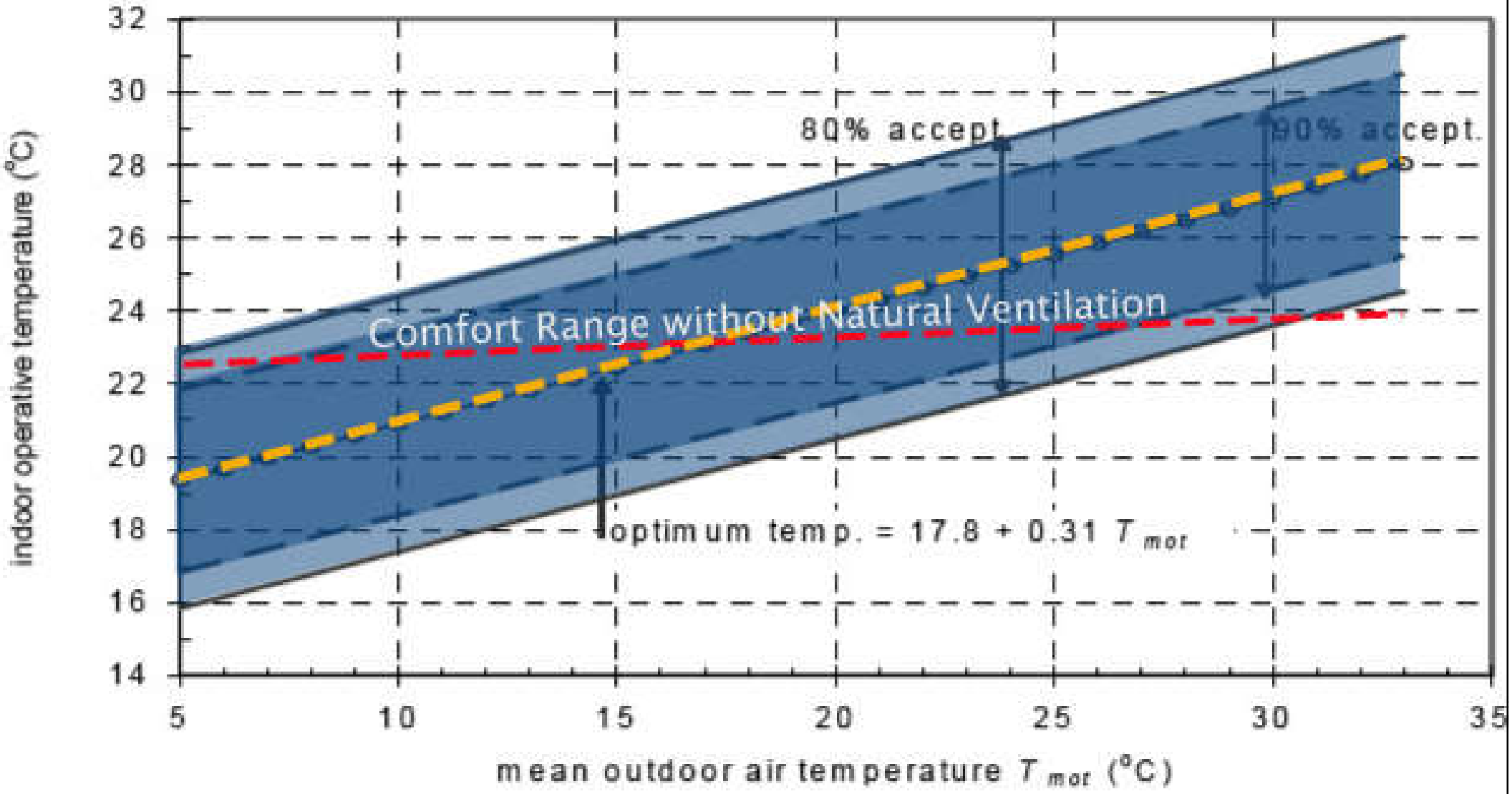


(Source: www.ashrae.org)



(Source: CBE Thermal Comfort Tool for ASHRAE-55 http://comfort.cbe.berkeley.edu/)

Adaptive comfort range recreated from ASHRAE Standard 55



(Source: https://lunablogs.wordpress.com/1994/05/15/luxury-resort-jaisalmer-india/)

ASHRAE Standard 55

- To demonstrate compliance the following must be documented, where applicable (a sample is provided in Informative Appendix J)
  - 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

ASHRAE Standard 55

- 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 (e.g. Chapter 57 of the ASHRAE Handbook-HVAC Applications)

ASHRAE Standard 55

- 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

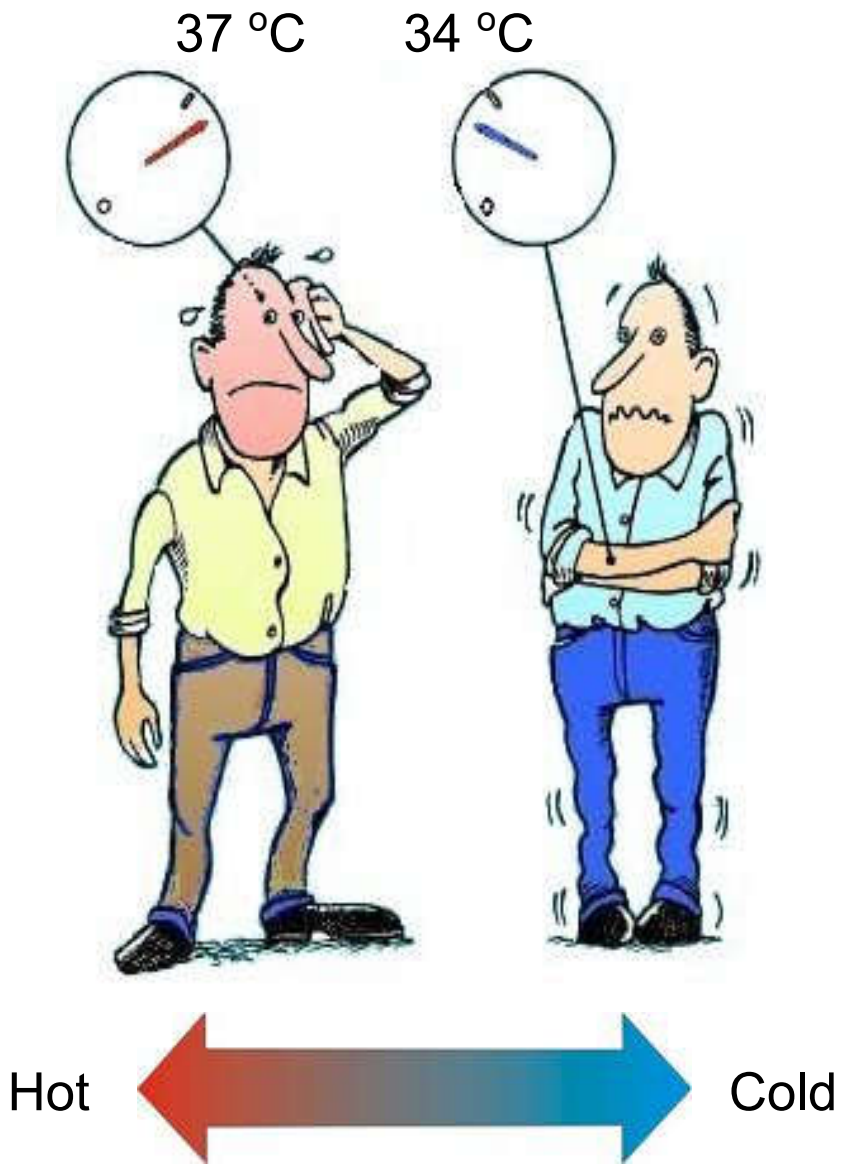
What is Thermal Comfort?

Definition

…hat condition of mind which expresses satisfaction with the thermal environment.

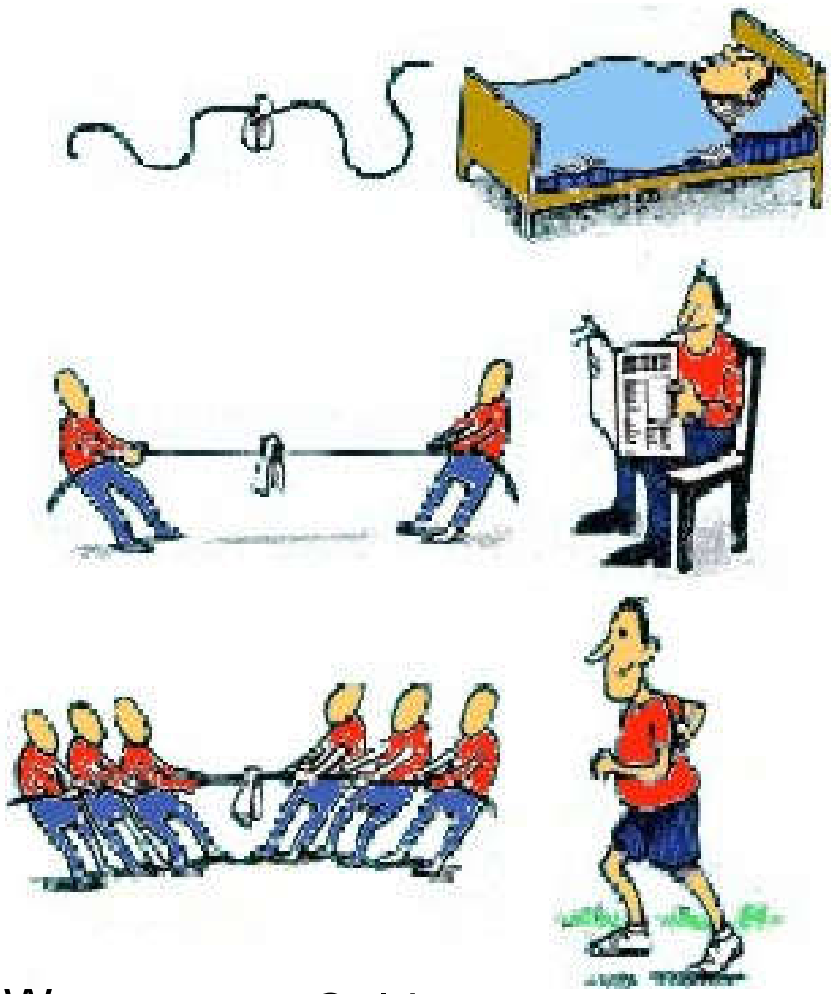
ISO 7730

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).

Perception of Thermal Environment



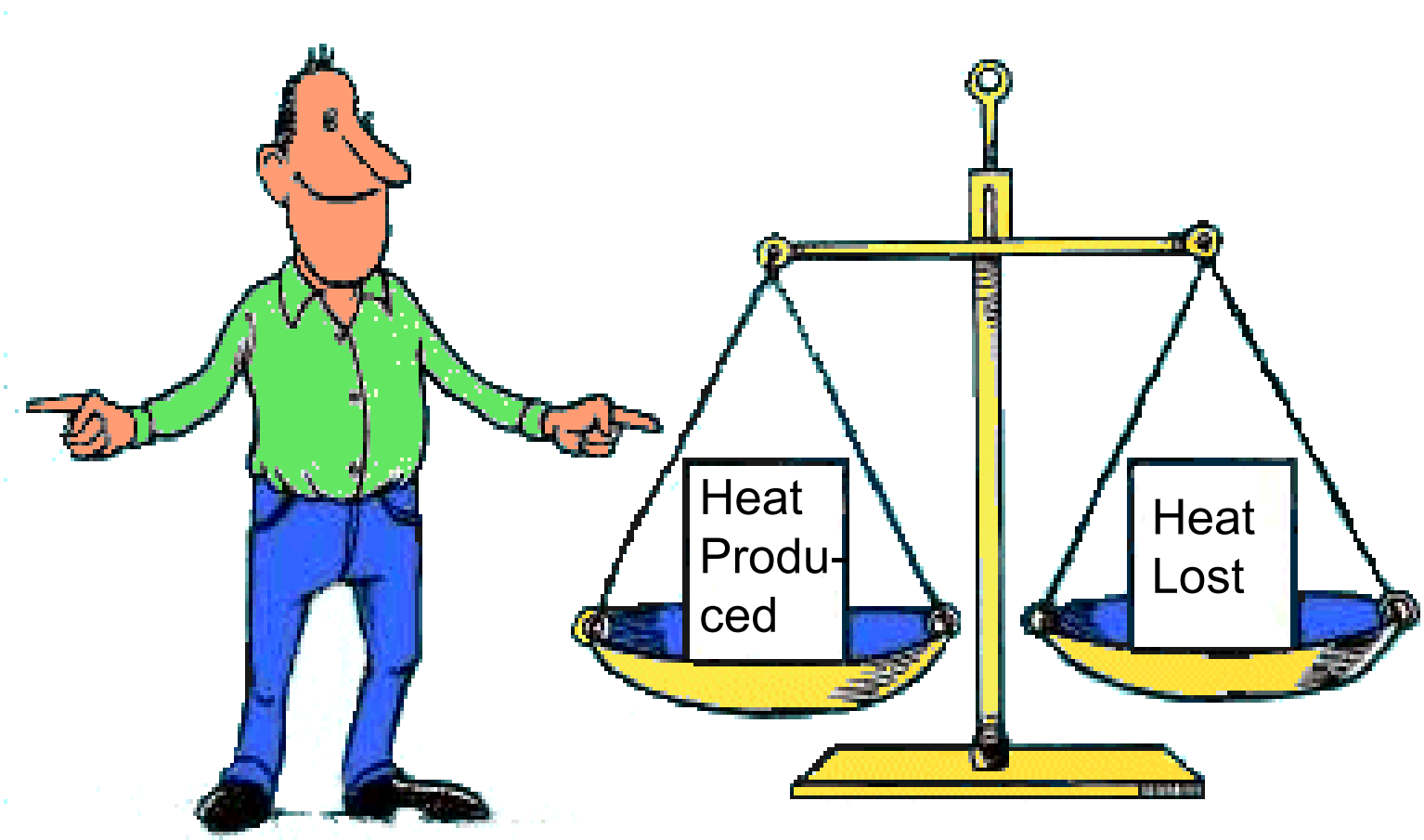
Warm impulses

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.

Heat Balance Equation

- General heat balance

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

where

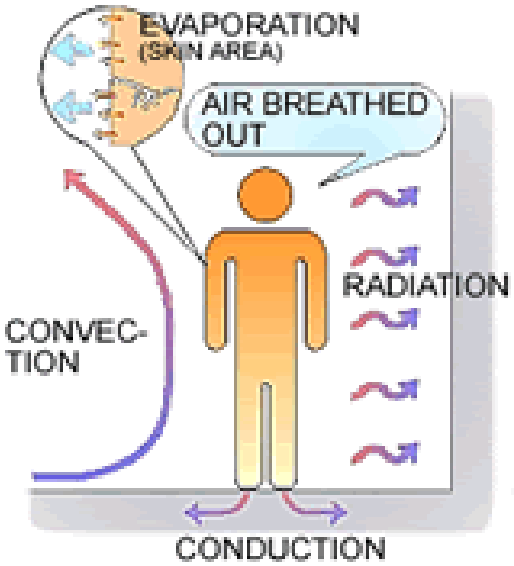
S = rate of heat storage of human body

M = metabolic rate

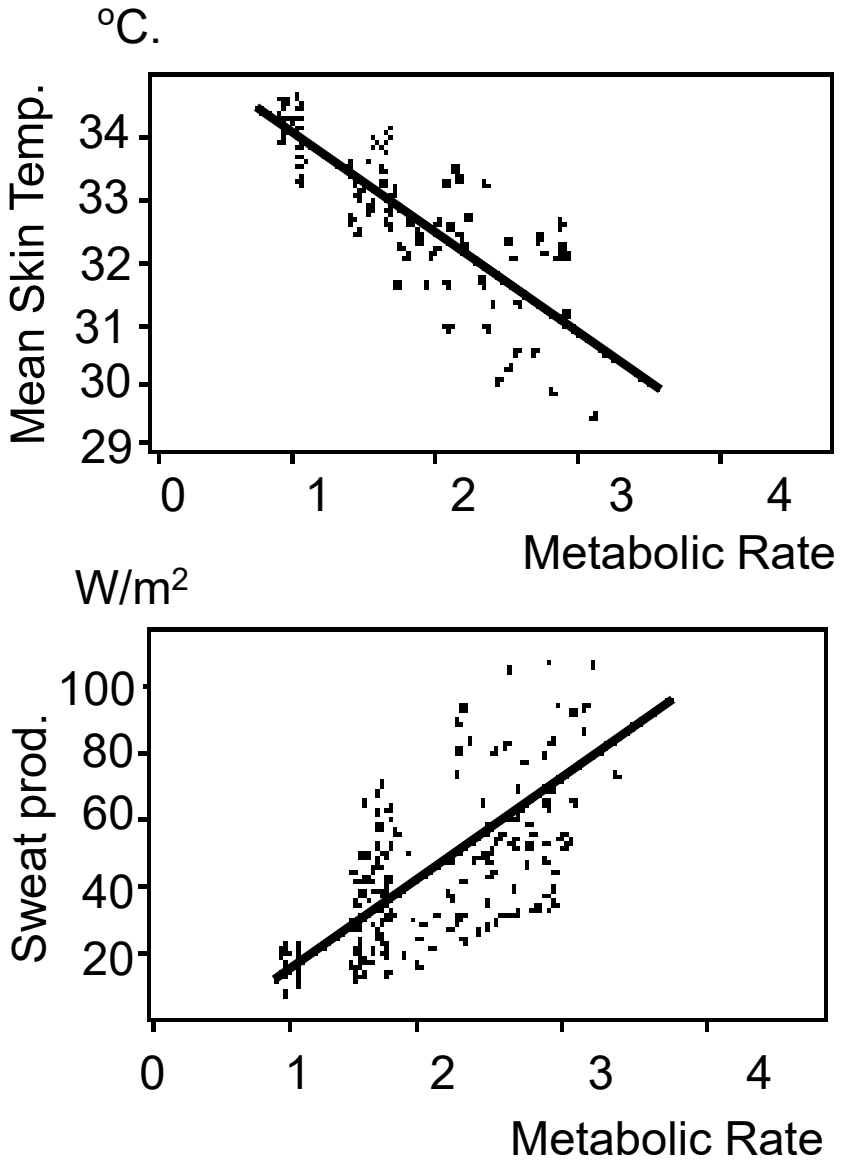
W = mechanical work done by human body

E = rate of total evaporation loss

R + C = dry heat exchange through radiation & convection



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.

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)

Predication of Thermal Comfort

- 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. (°C)

t_{db} = dry-bulb temp. (°C)

P_s = water vapour pressure (kPa)

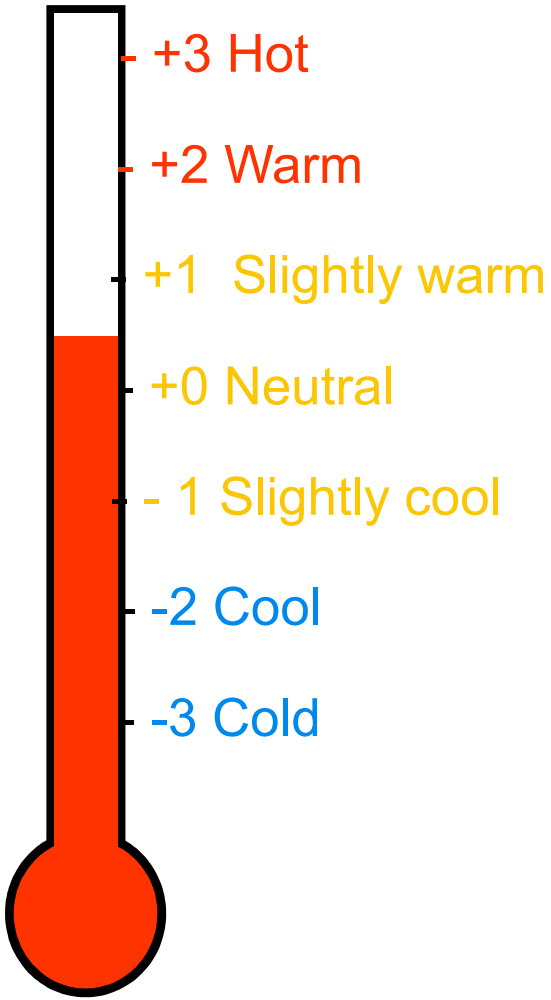
Predication of Thermal Comfort

- 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)

Predication of Thermal Comfort

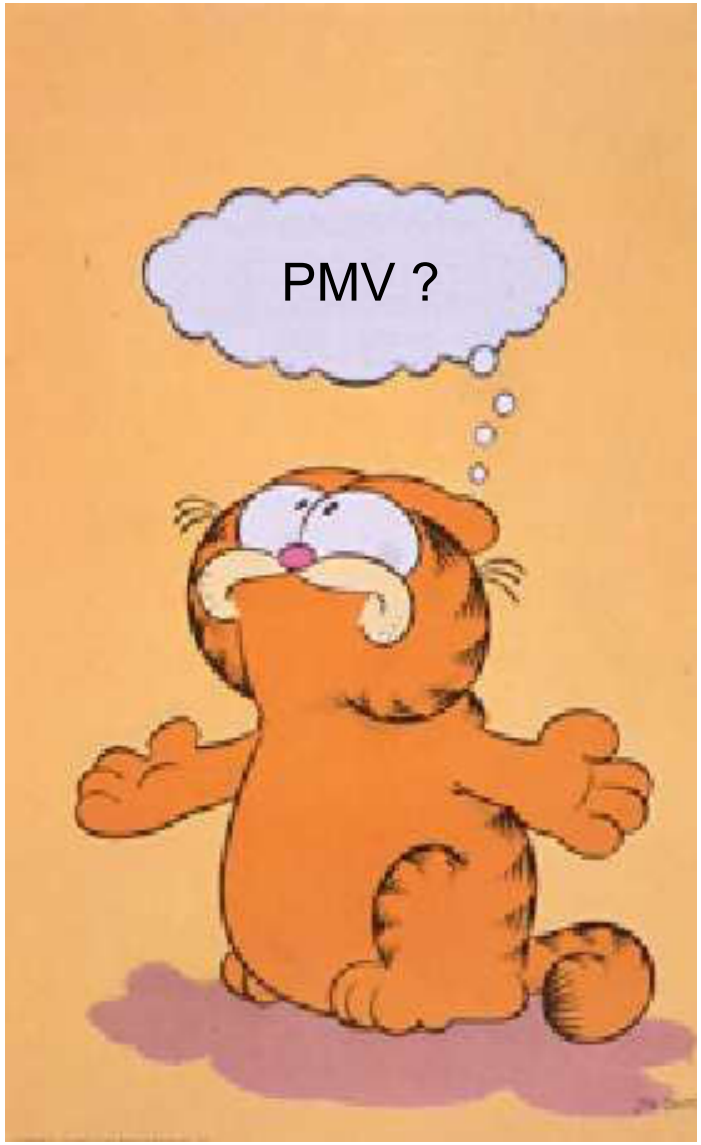
- **PMV**
  - a complex function of six major comfort parameters;
  - predict mean value of the subjective ratings of a group of people in a given environment
- **PPD**
  - determined from PMV as a quantitative measure of thermal comfort
  - ‘dissatisfied’ means not voting -1, +1 or 0 in PMV
  - normally, PPD < 7.5% at any location and LPPD < 6%

Predicted Mean Vote scale



The PMV index is used to quantify the degree of discomfort

Calculation of PMV index



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

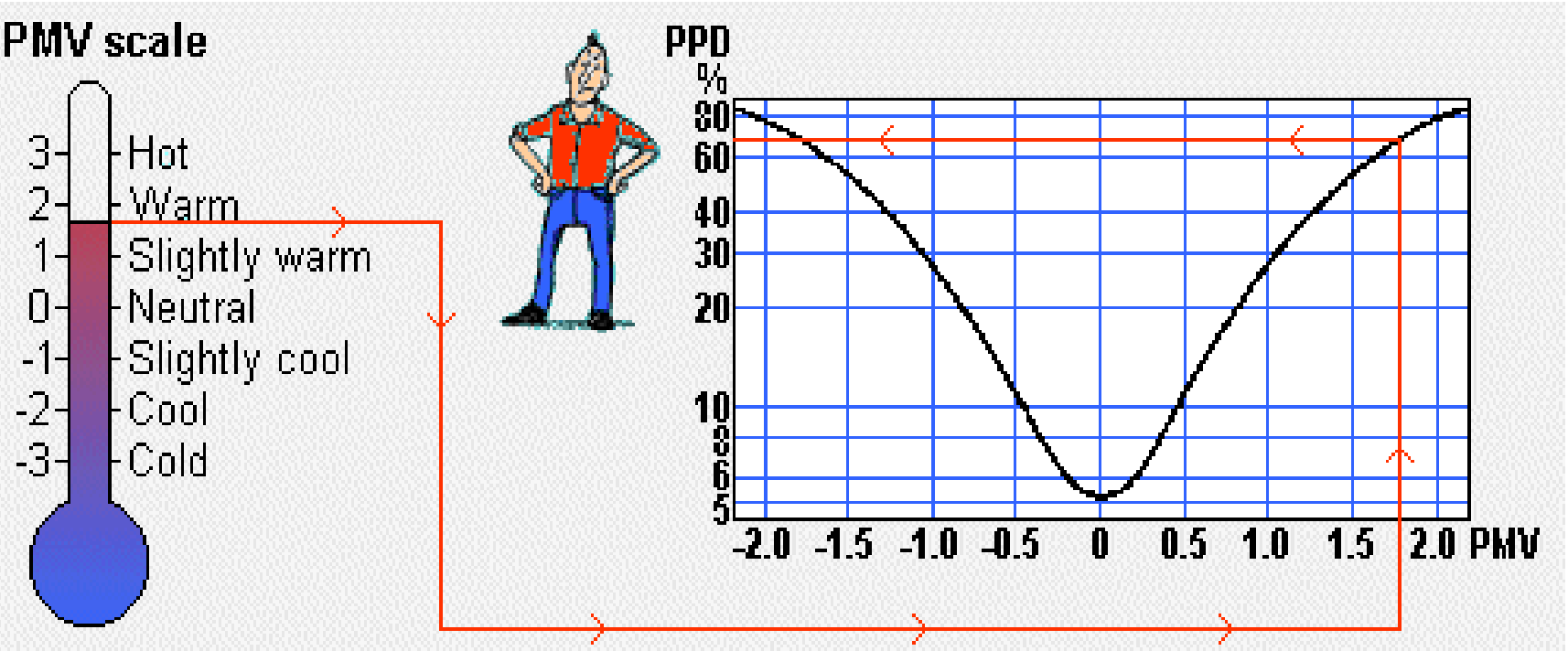
$$\Longrightarrow$$

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

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

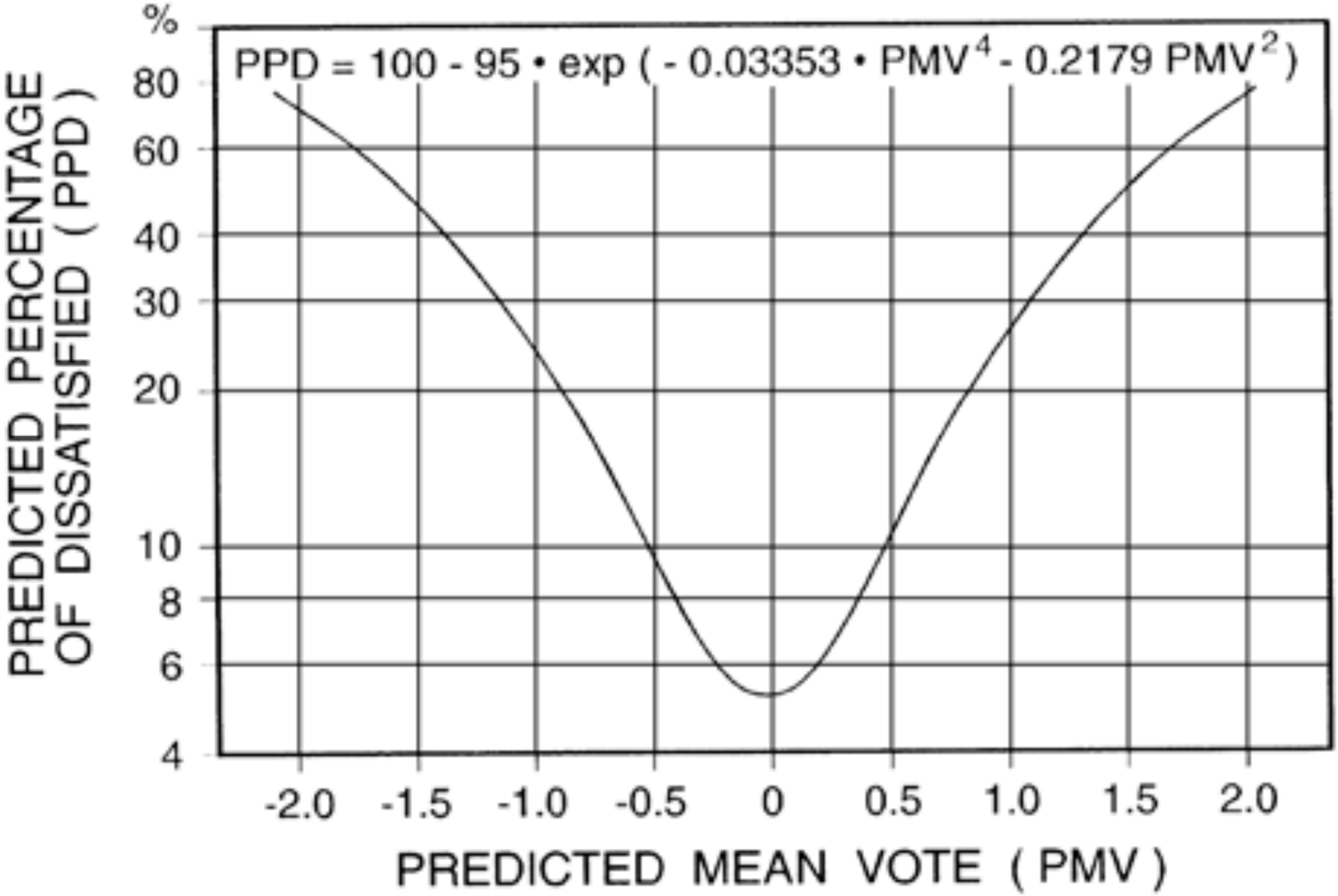
M [MET] Icl [CLO]

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)

Predication of Thermal Comfort

- Comfort zones
  - defined using isotherms parallel to 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
    - for summer, 22.8 ^{o}C ≤ SET ≤ 26.1 ^{o}C
    - for winter, 20.0 ^{o}C ≤ SET ≤ 23.9 ^{o}C

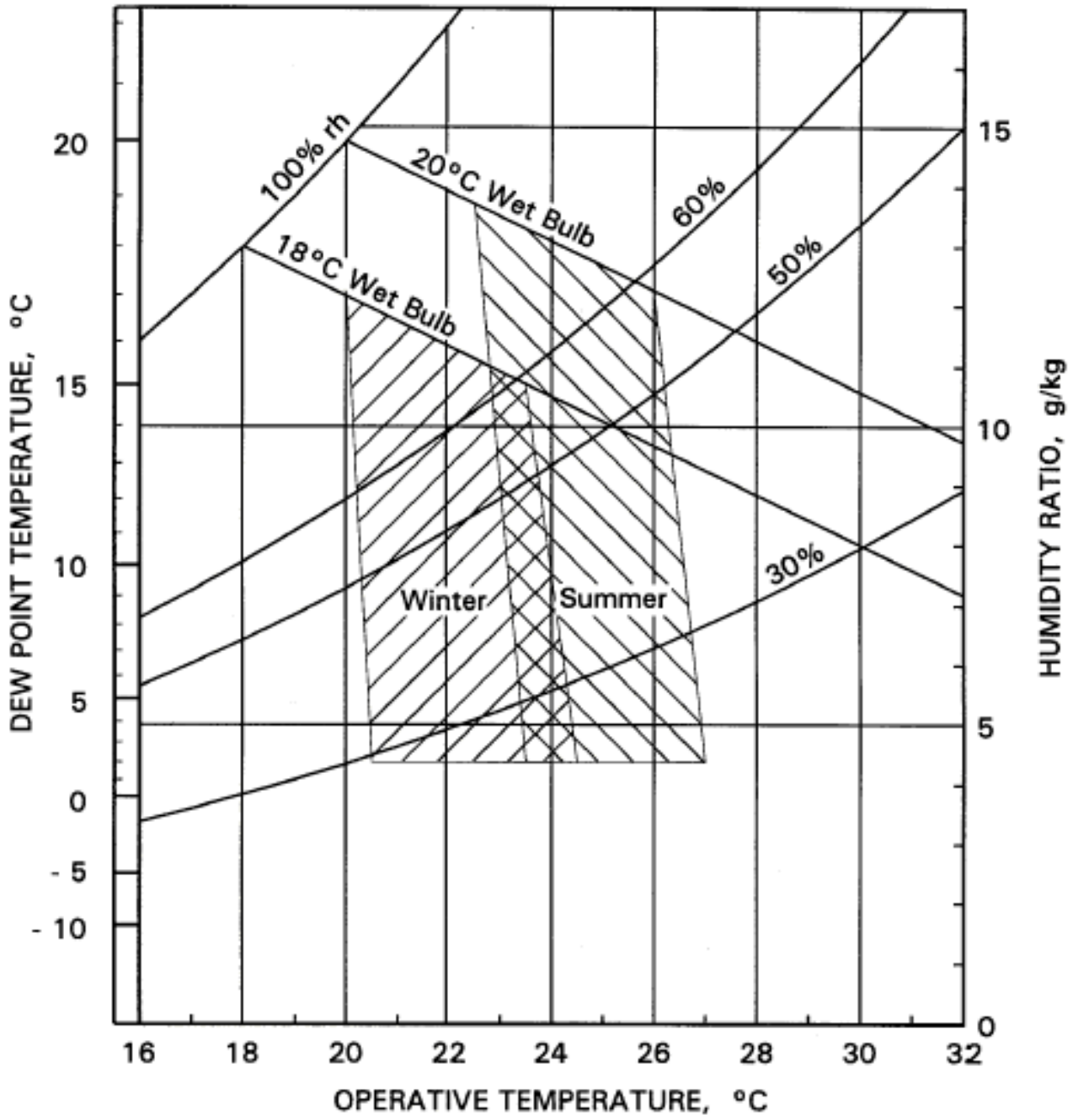
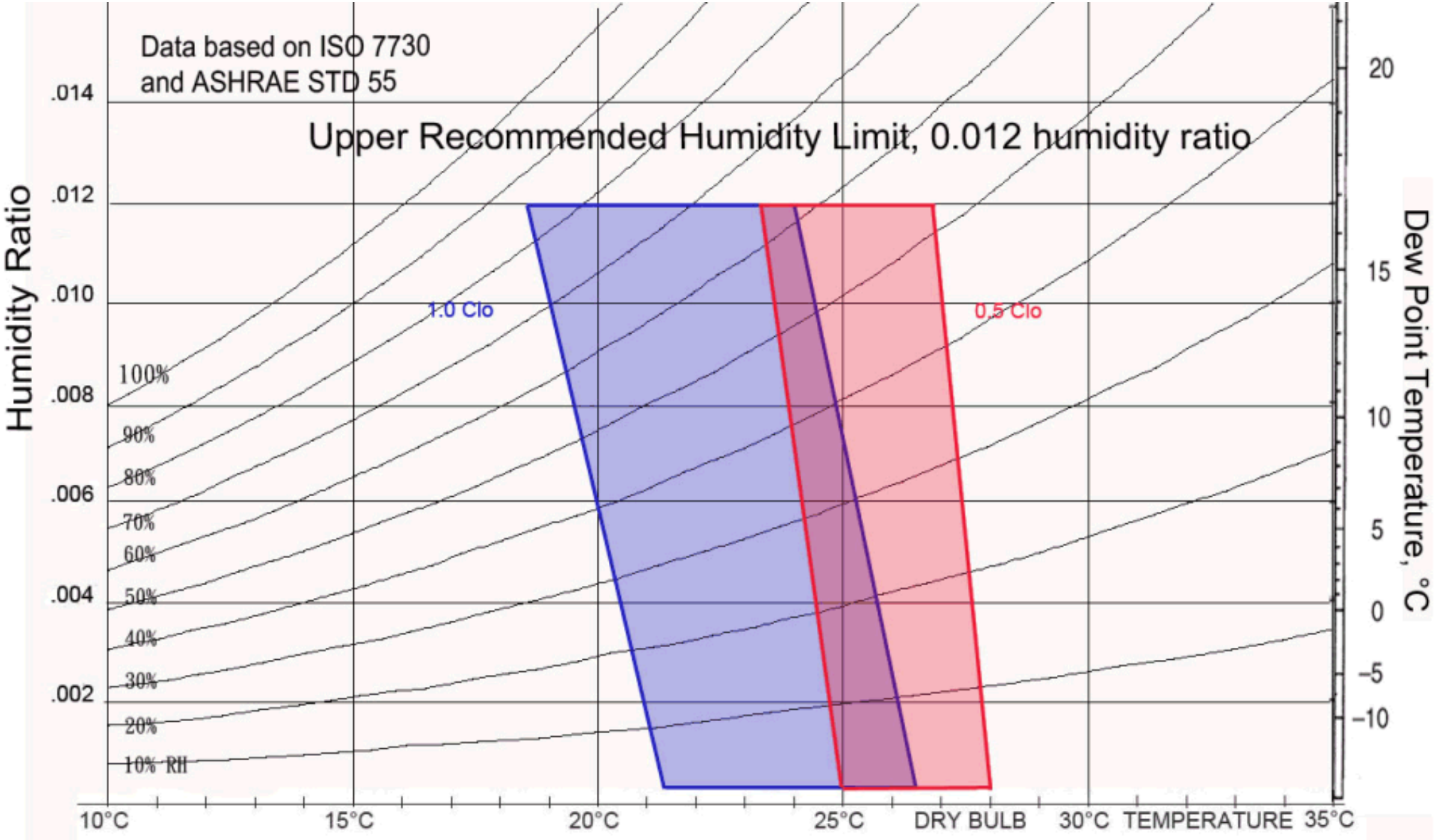


Fig. 5 ASHRAE Summer and Winter Comfort Zones

(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)



Influencing Factors

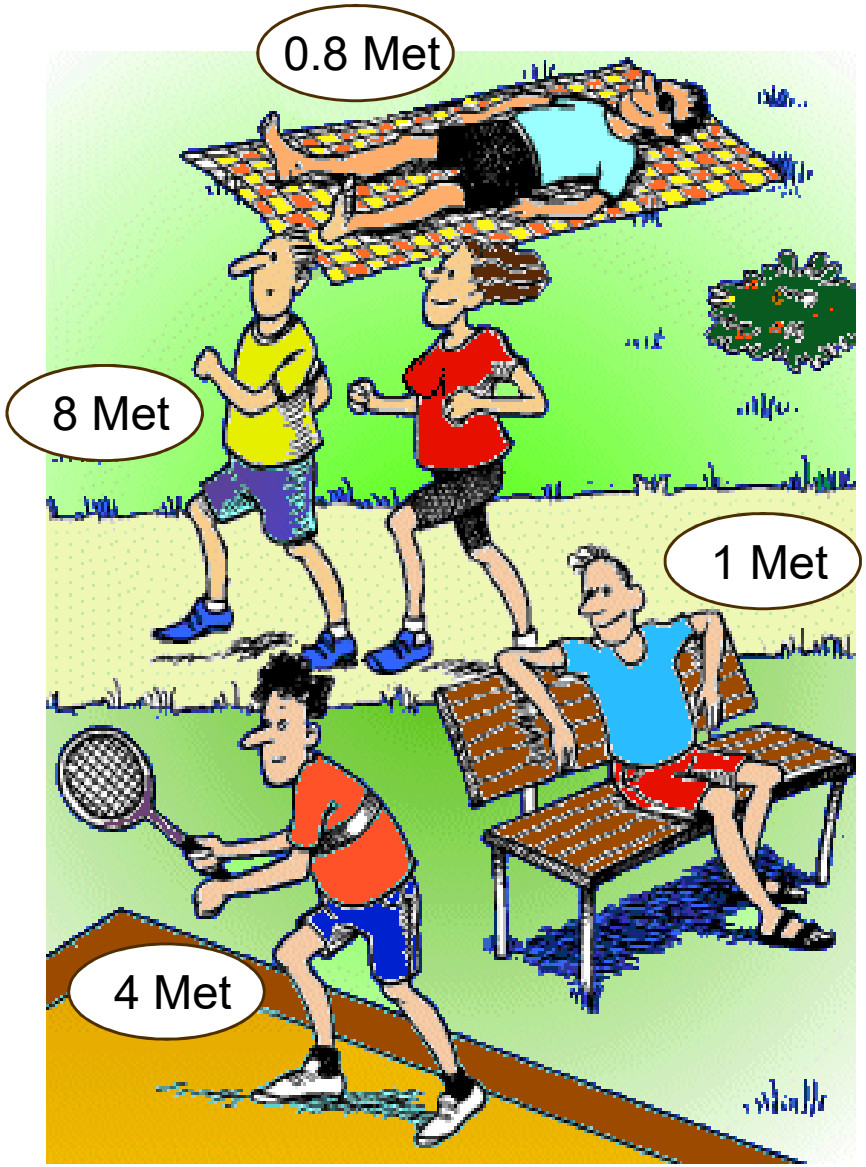
- Environmental factors:
  - Dry-bulb temperature (also related to humidity)
  - Relative humidity (or water vapour pressure)
    - Influences evap heat loss and skin wettedness
    - Usually RH between 30% and 70% is comfortable
  - Air velocity (increase convective heat loss)
    - Preferable air velocity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

What should be Estimated?

- Parameters to estimate and calculate are:

Met	Estimation of Metabolic rate
Clo	Calculation of Clo-value

Metabolic Rate



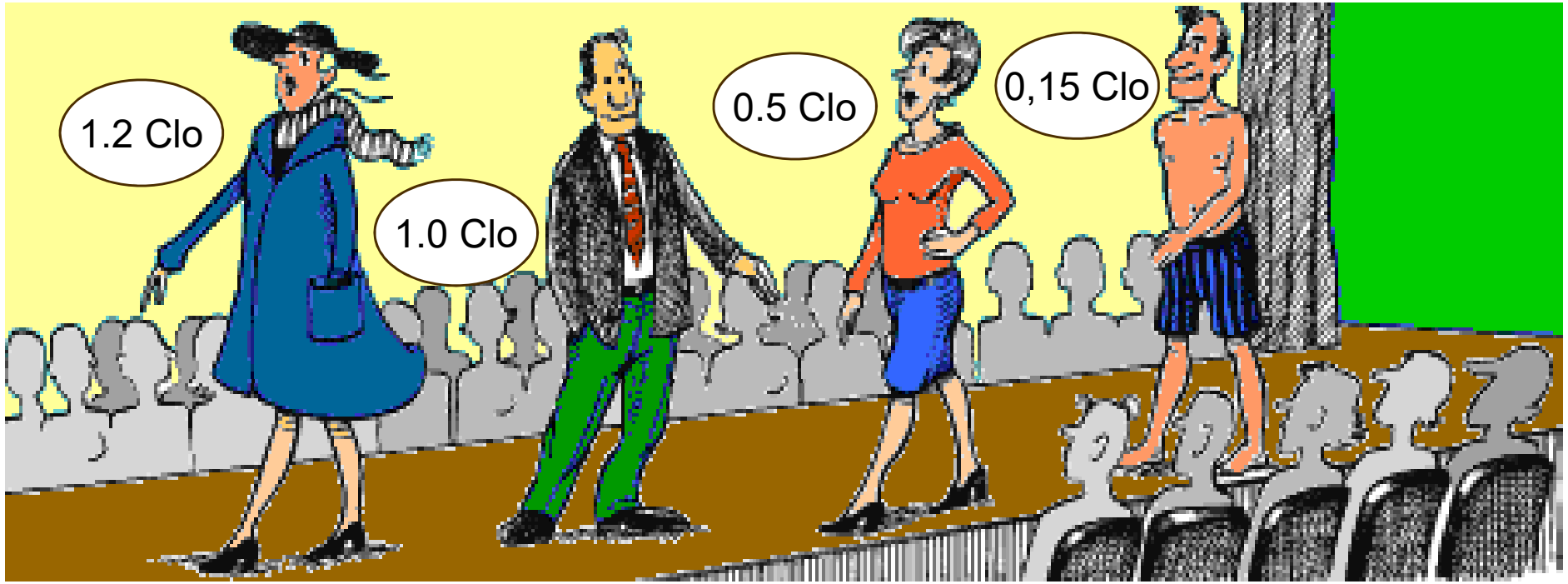
- Energy released by metabolism depends on muscular activity.
- Metabolism is measured in Met (1 Met=58.15 W/m^2 body surface).
- Body surface for normal adult is 1.7 m^2.
- A sitting person in thermal comfort will have a heat loss of 100 W.
- Average activity level for the last hour should be used when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

Calculation of Insulation in Clothing



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

Clo Values Table

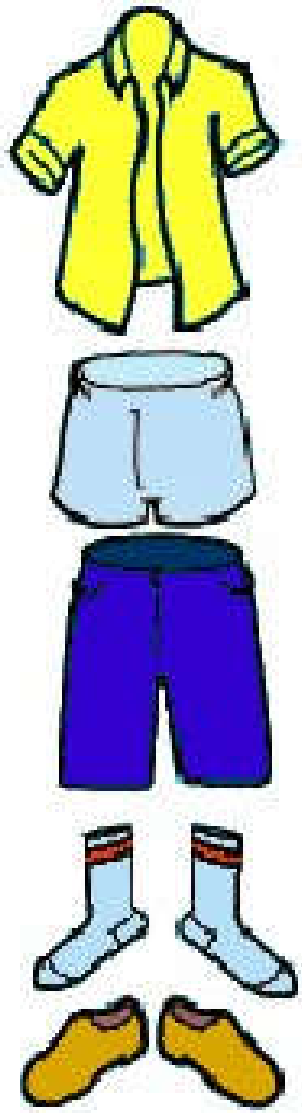
Garment description		**I_{clu} Clo**	**I_{clu} m^2 ◦C/W**
Underwear	Pantyhose	0.02	0.003
	Briefs	0.04	0.006
	Pants long legs	0.10	0.016
Underwear, shirts	Bra	0.01	0.002
	T-shirt	0.09	0.014
	Half-slip, nylon	0.14	0.022
Shirts	Tube top	0.06	0.009
	Short sleeves	0.09	0.029
	Normal, long sleeves	0.25	0.039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

Clo Values Table

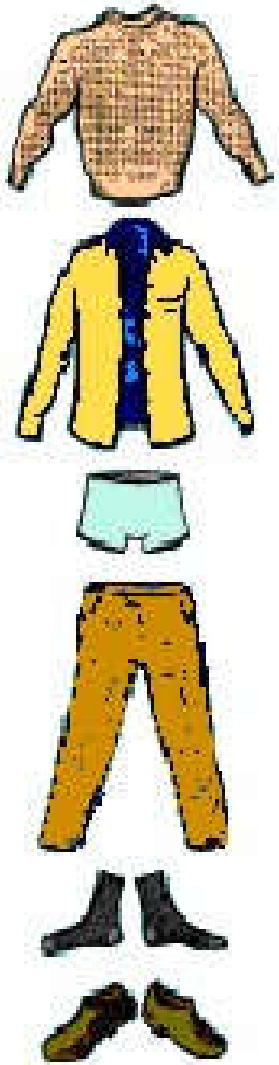
Garment description		I_{clu} Clo	I_{clu} m^2 ◦C/W
Jackets	Vest	0.13	0.020
	Jacket	0.35	0.054
Coats over-trousers	Coat	0.60	0.093
	Parka	0.70	0.109
	Overalls	0.52	0.081
Sundries	Socks	0.02	0.003
	Shoes (thin soled)	0.02	0.003
	Boots	0.10	0.016
	Gloves	0.05	0.008
Skirt, dresses	Light skirt, 15cm above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

Calculation of Clo-value (Clo)

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

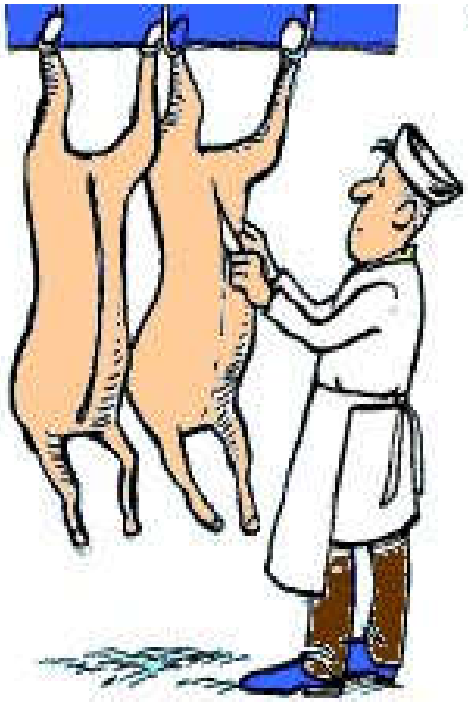


0.19 + 0.04 + 0.11 + 0.02 + 0.02 = 0.38



0.28 + 0.25 + 0.04 + 0.25 + 0.05 + 0.04 = 0.91

Comfort Temperature, t_{co} (typical)



1.7 clo
2.5 Met
RH=50%
t_{co}=6ºC

0.8 clo
2.2 Met
RH=50%
t_{co}=18ºC

0.5 clo
1.2 Met
RH=50%
t_{co}=24,5ºC

What should be measured?

- Parameters to measure are:

  - t_a Air Temperature
  - t_r Mean Radiant Temperature
  - v_a Air Velocity
  - p_a Humidity

Collection of Thermal Comfort Data

Transducers

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

Workplace Measurements

- 1.1 m

- 0.6 m

- 0.1 m

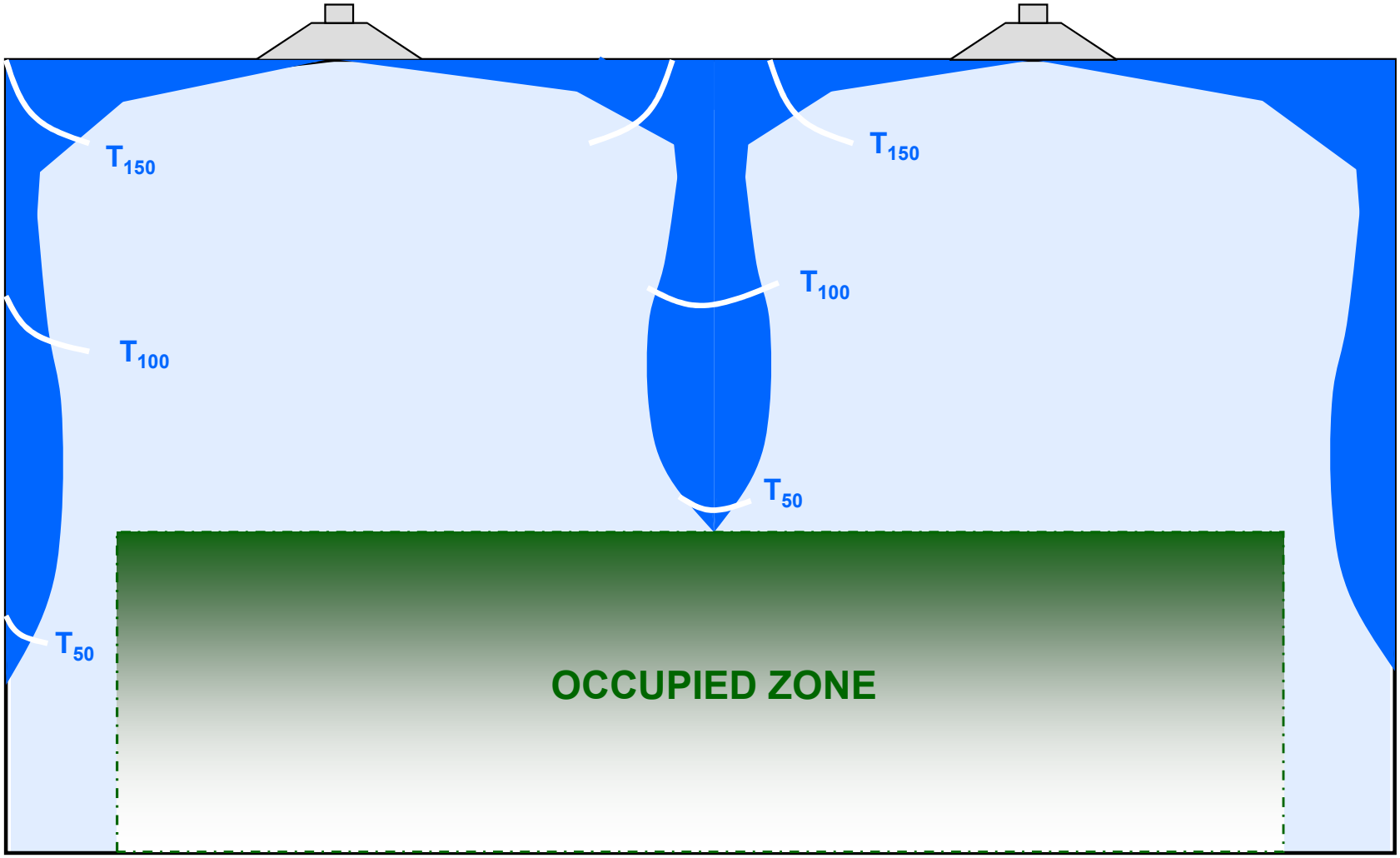
- 1.7 m

- 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



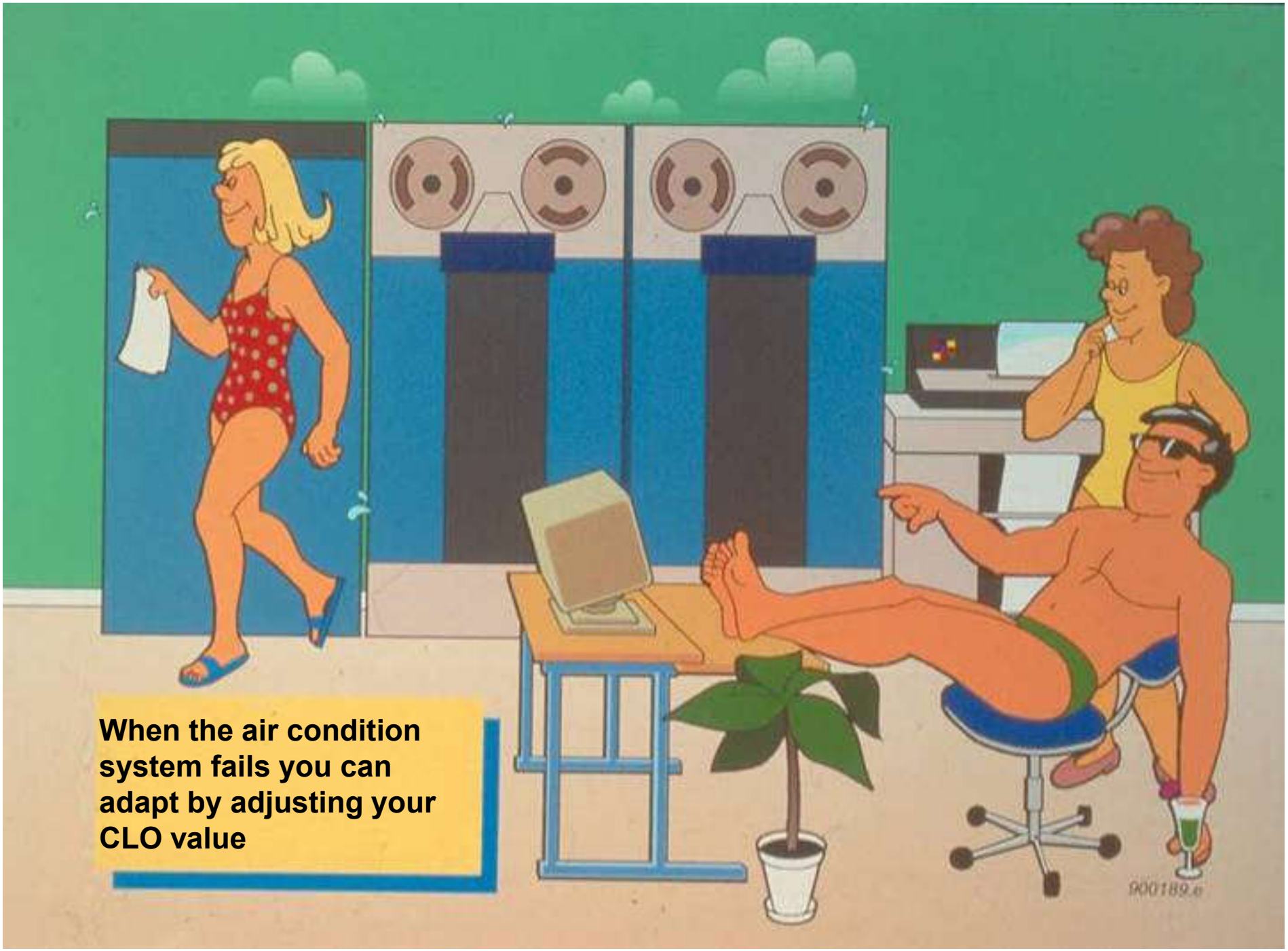
Influencing Factors

- 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

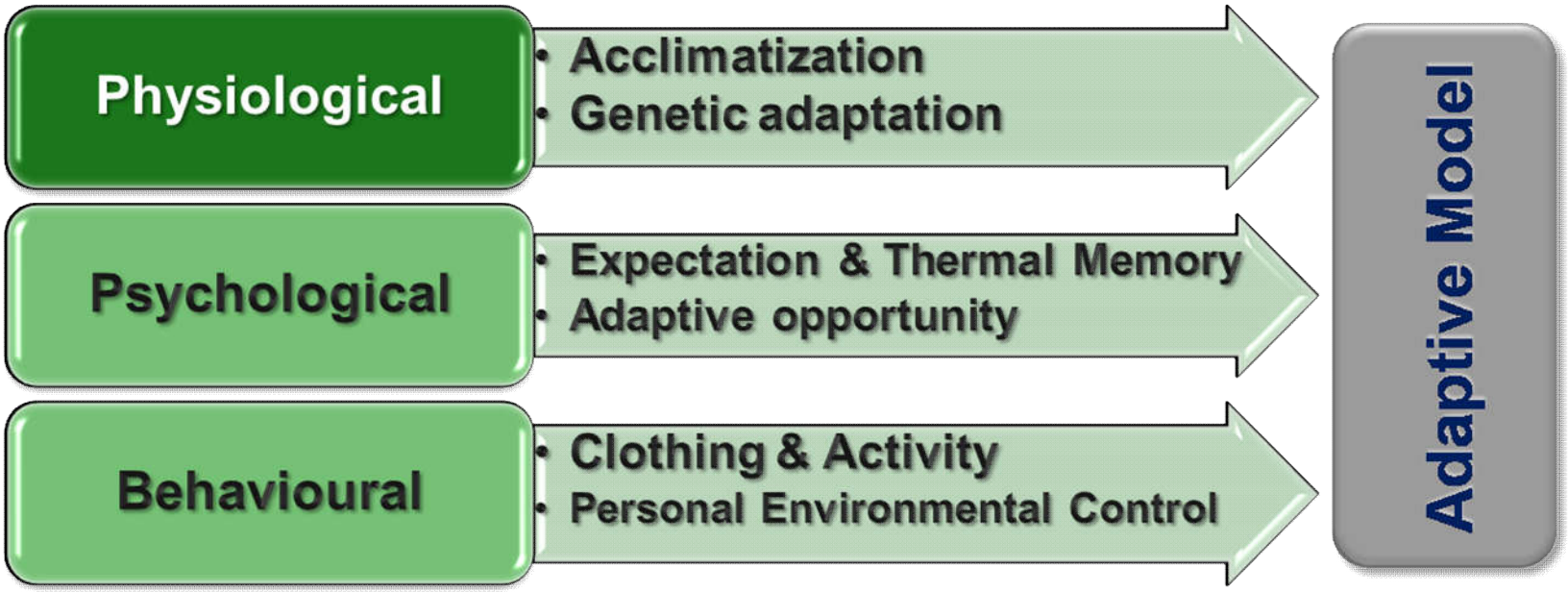
Adaptation need not be a conscious act, and not only for human

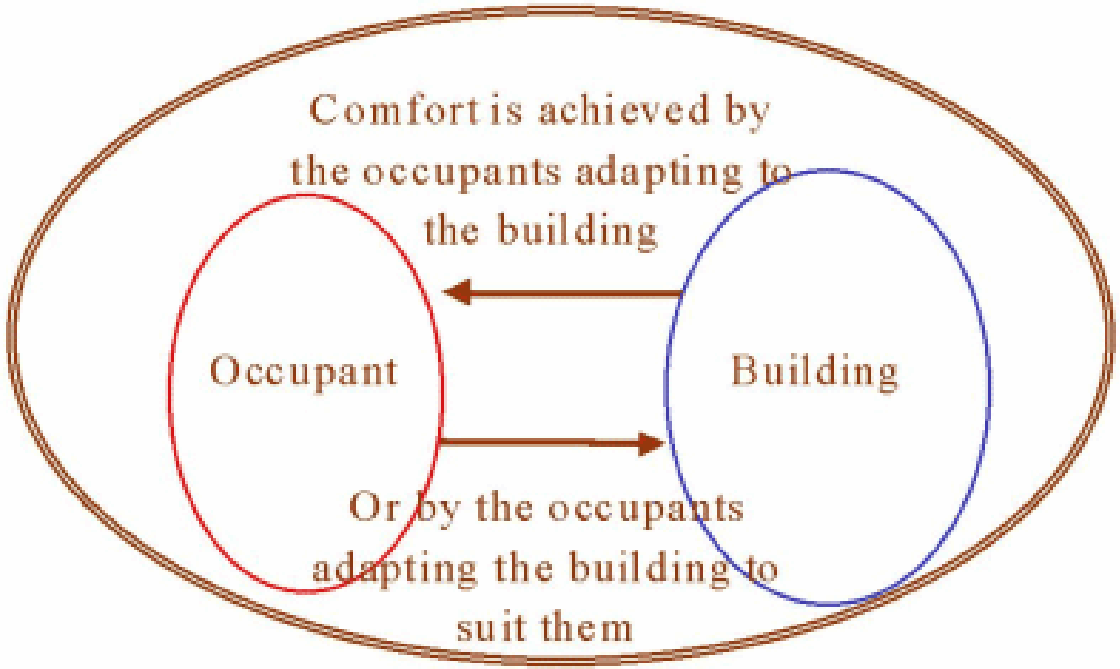
(Source: Nicol, F., Humphreys, M. and Roaf, S., 2012. *Adaptive Thermal Comfort: Principles and Practice*)

Acclimatisation/Adaptation!



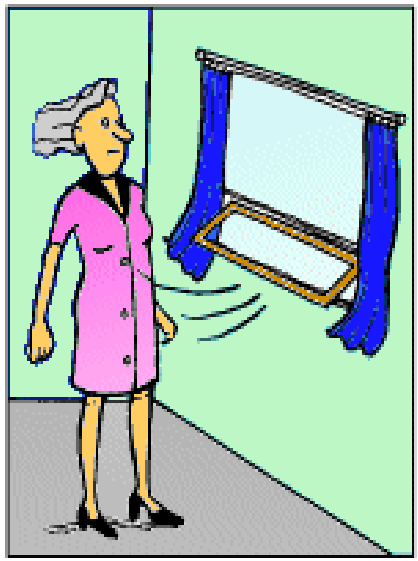
Basic concepts of adaptive thermal comfort





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

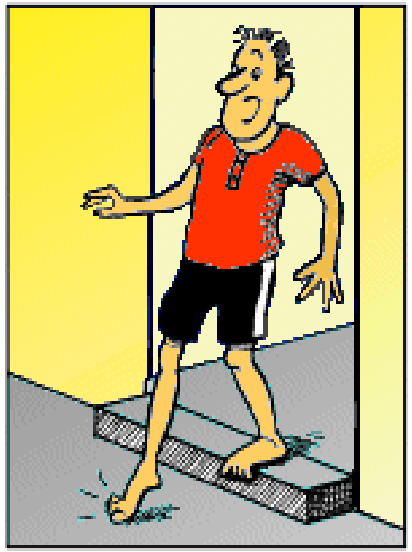
Local Thermal Discomfort



- Draught

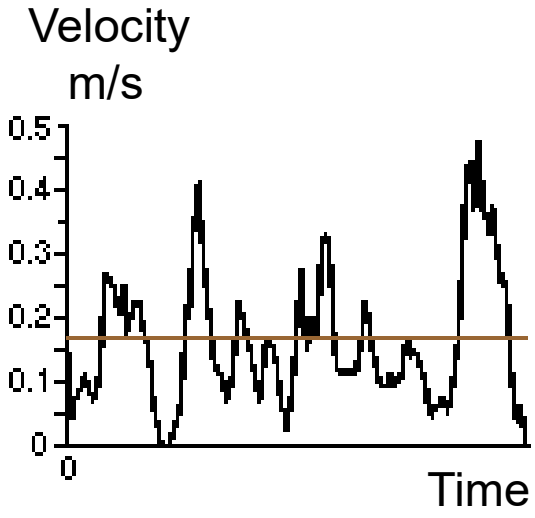
- Radiation Asymmetry

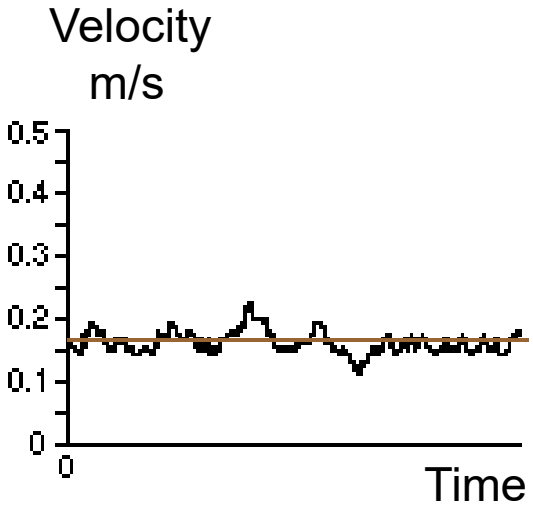
- Vertical Air Temperature Differences.

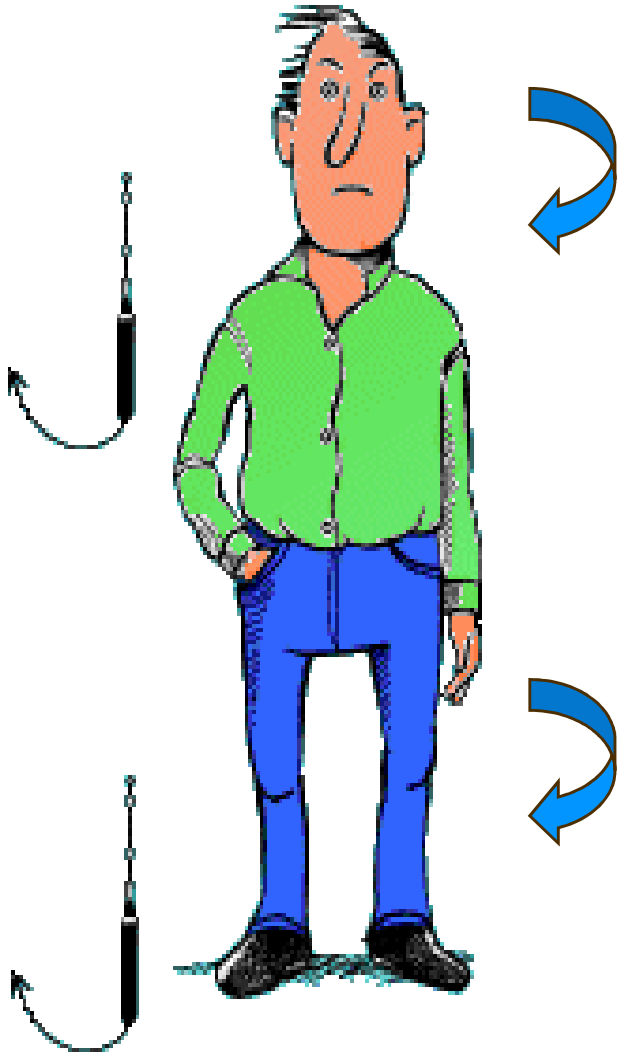


- Floor temperature

Draught

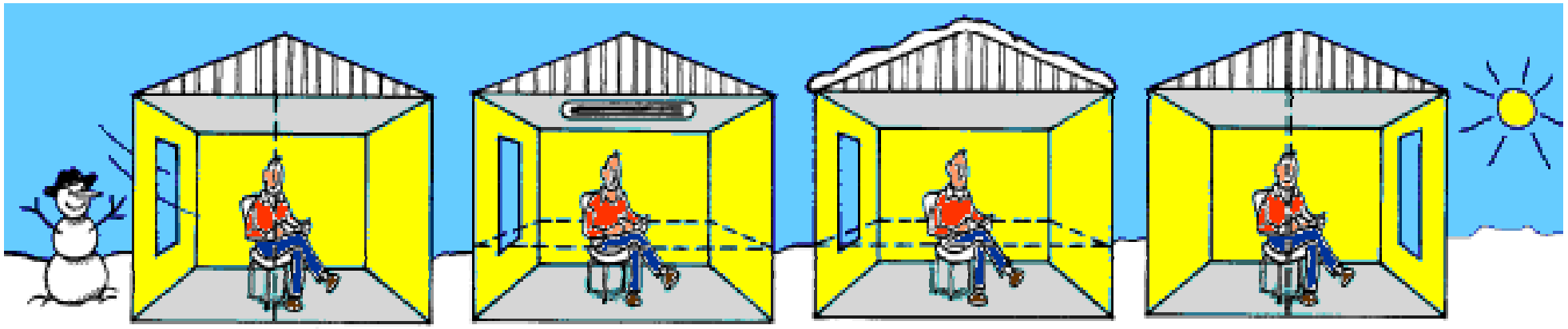


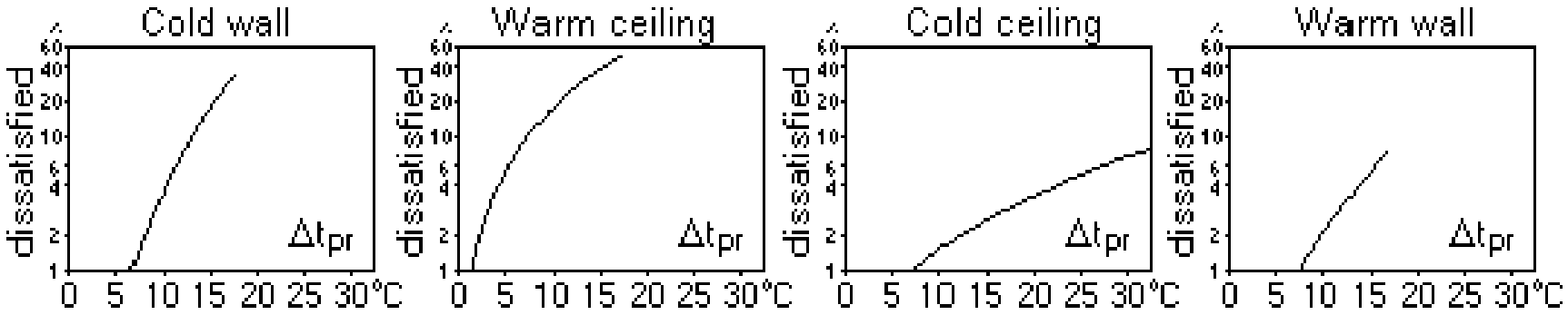




- Draught is the most common complaint indoors
- What is felt is Heat Loss
- Heat Loss is depending on average Air Velocity, Temperature and Turbulence
- High Turbulence is more uncomfortable, even with the same Heat Loss

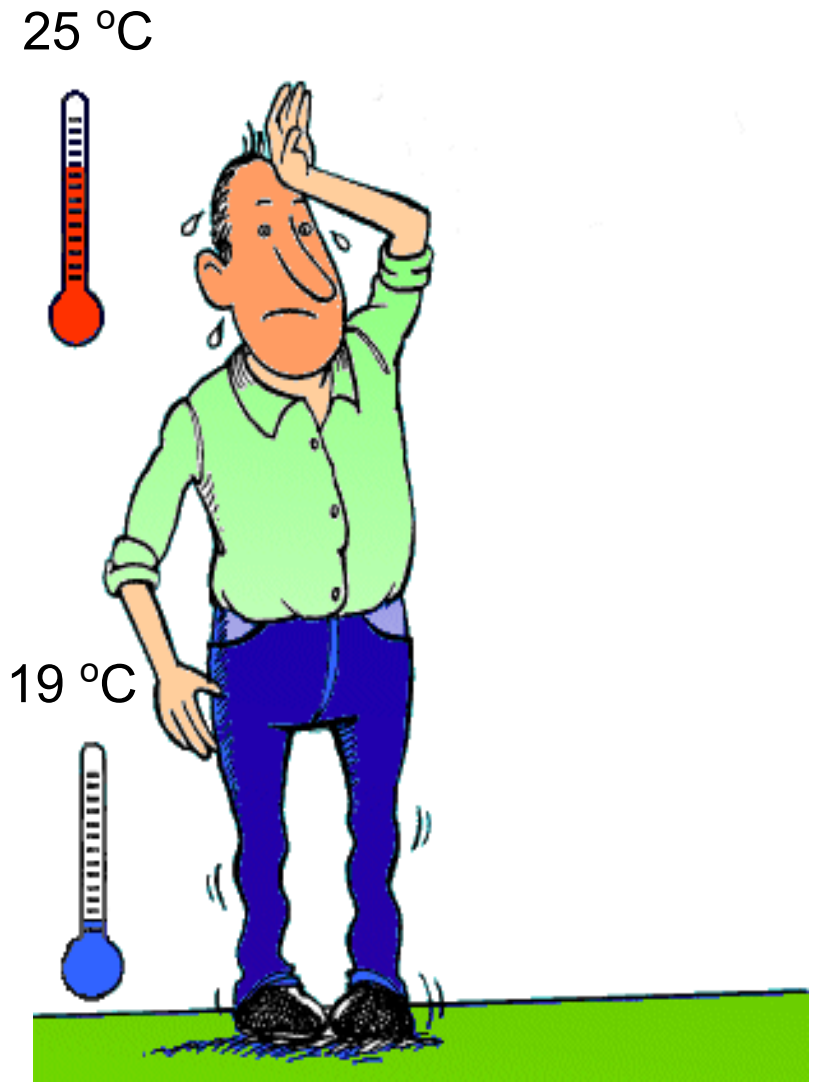
Radiation Asymmetry

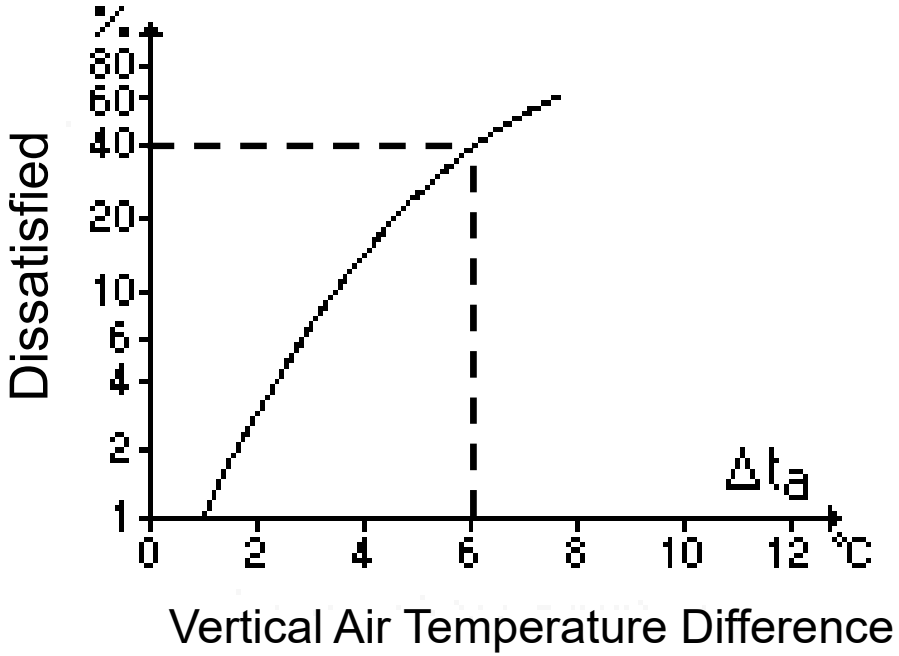




- Radiant Temperature Asymmetry is perceived uncomfortable
- Warm ceilings and cold walls causes greatest discomfort

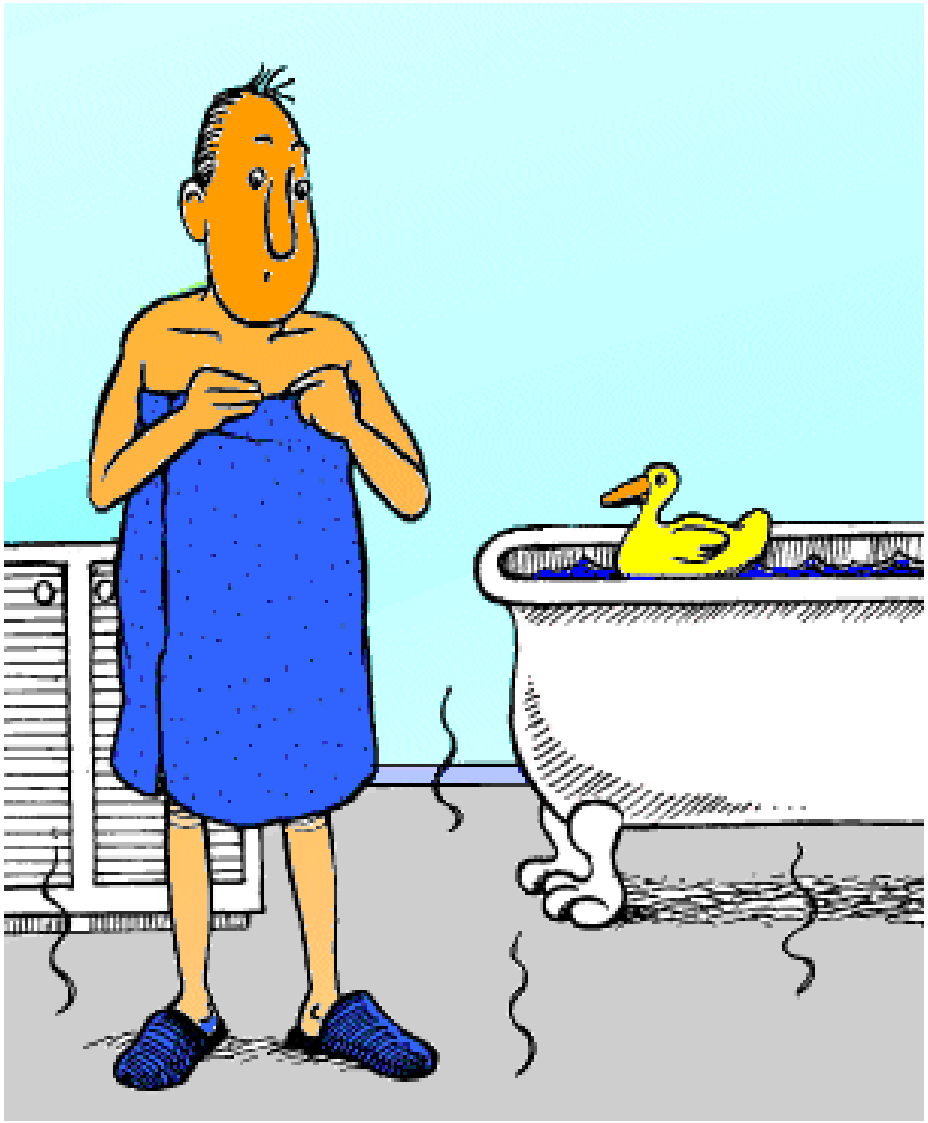
Vertical Air Temperature Difference

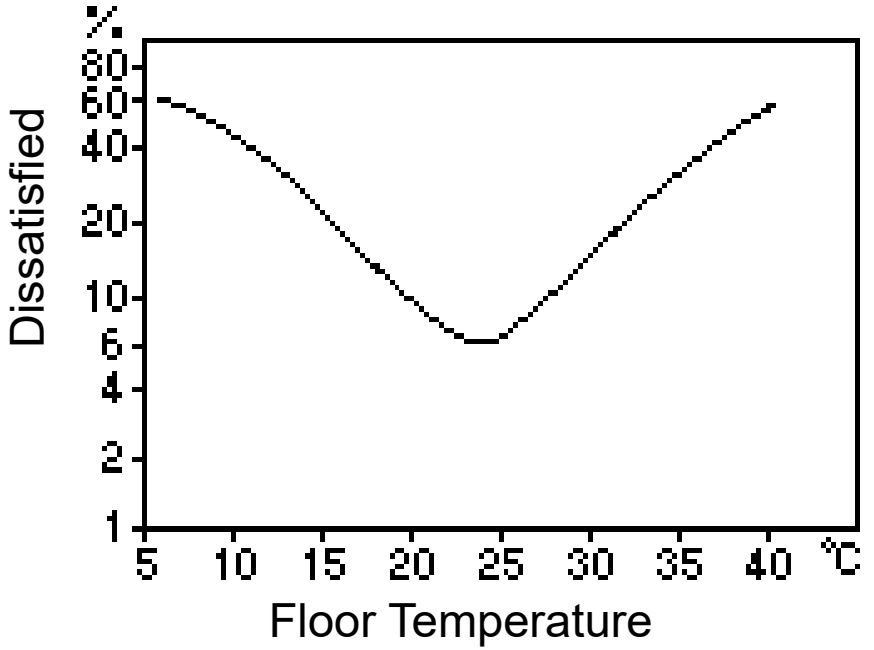




- Vertical Air Temperature Difference is the difference between Air Temperature at ankle and neck level

Floor Temperature





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

THANK YOU 謝謝 !!