Thermal Comfort

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Aug 2020

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Acknowledgements

- Cartoons and some figures are taken from:
  - INNOVA AirTech Instruments https://innova.lumasenseinc.com/

- The need to define "comfortable environment" arose from the air-conditioning industry
- Thermal comfort standards:
  - ASHRAE Standard 55
  - ISO 7730

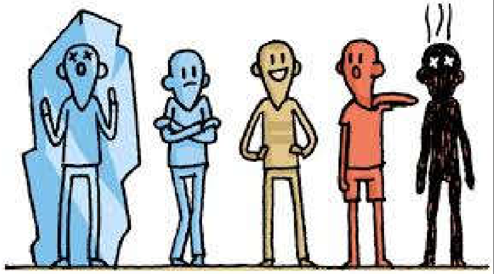
What is Thermal Comfort?

Definition

- That condition of mind
which expresses satisfaction
with the thermal environment.
ISO 7730

熱舒適性

What is Thermal Comfort?



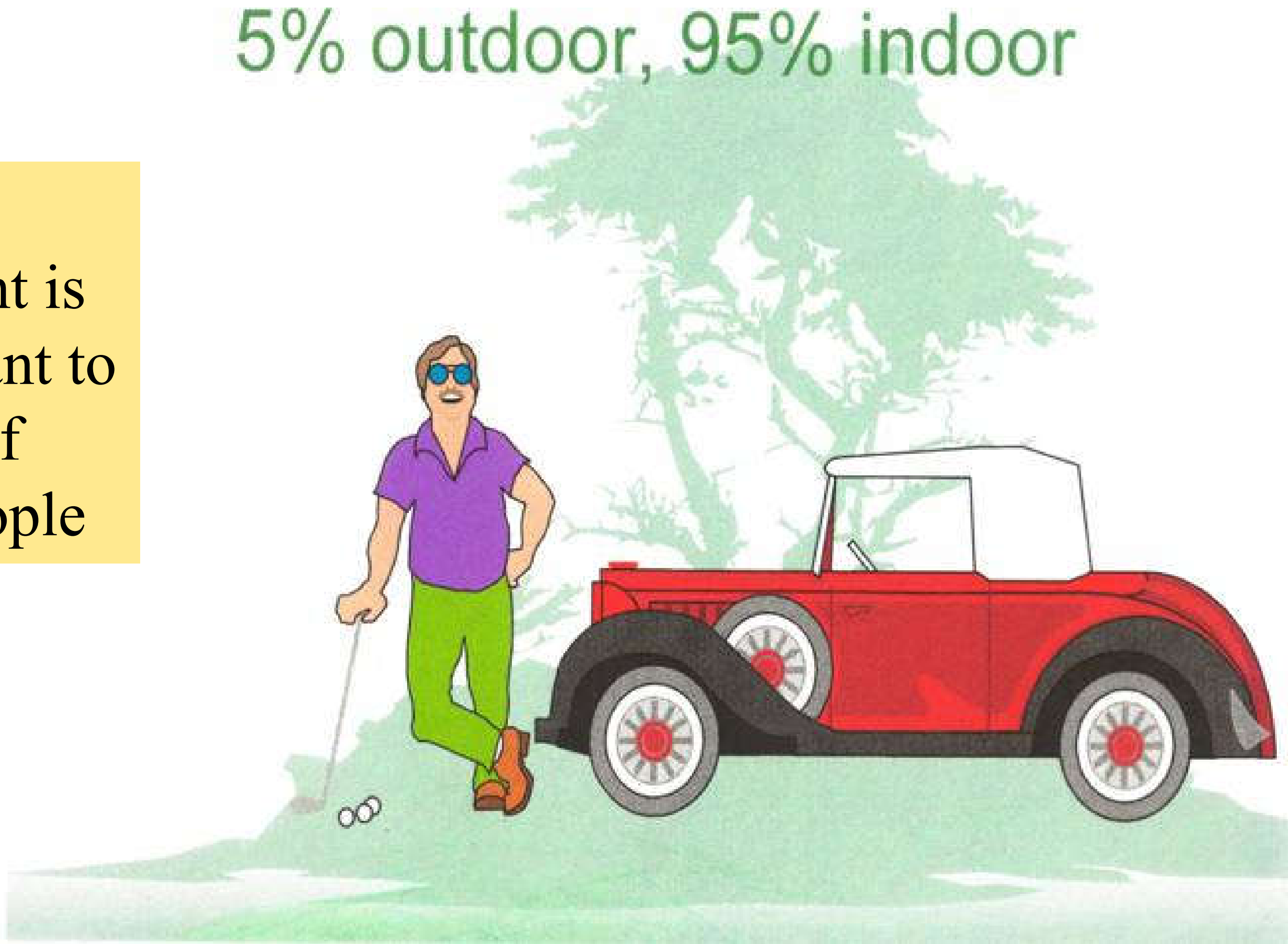
- Thermal comfort is experienced via a number of conscious interactions between three personal and environment factors
  - Physiological: the way our bodies work and interact with our environment
  - Physical: the main parameters of the environment around us (air temperature, air humidity, air movement, 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)

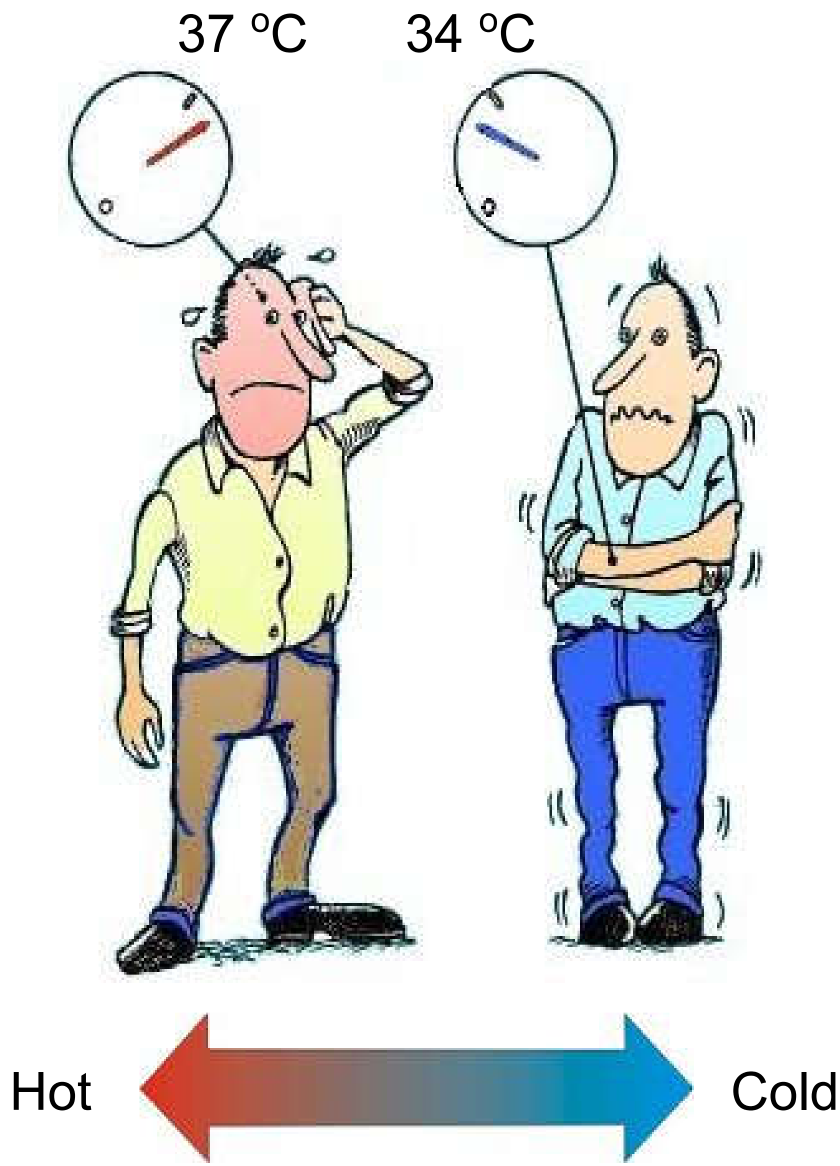
Thermal Environments

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

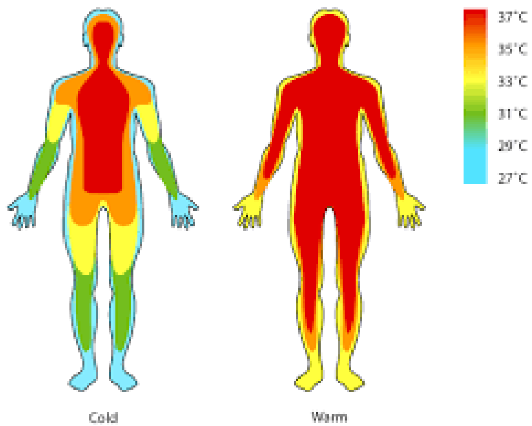
Indoor environment is very important to the life of modern people



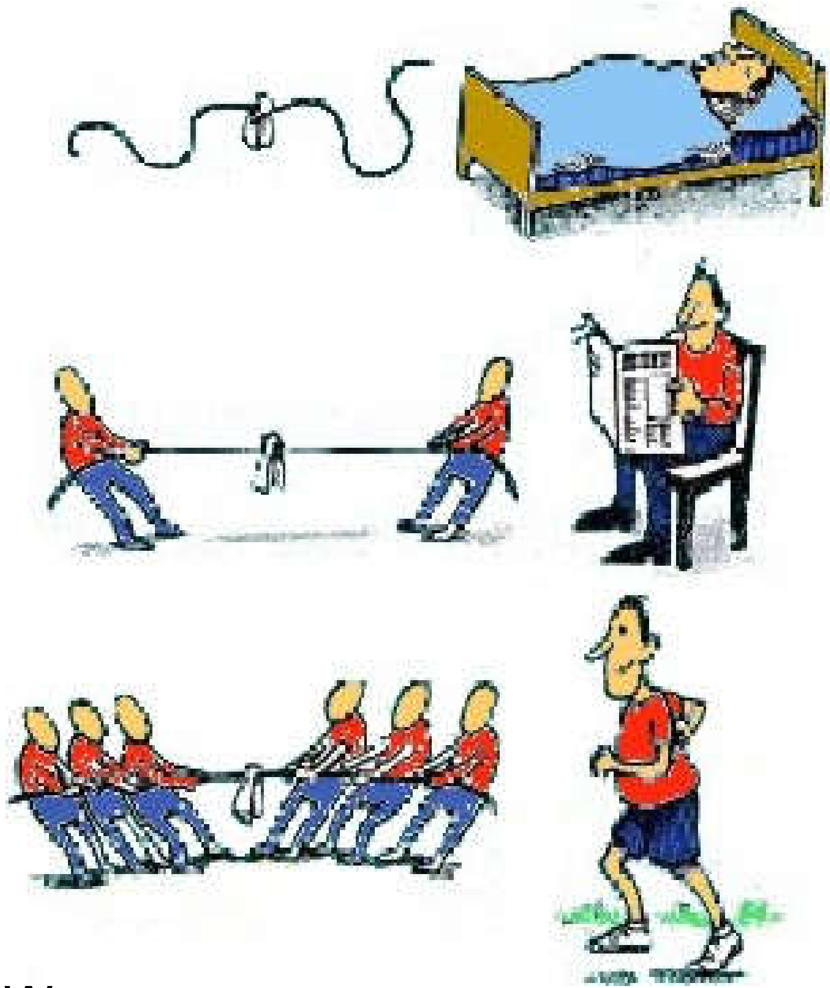
Body Temperature



- 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).



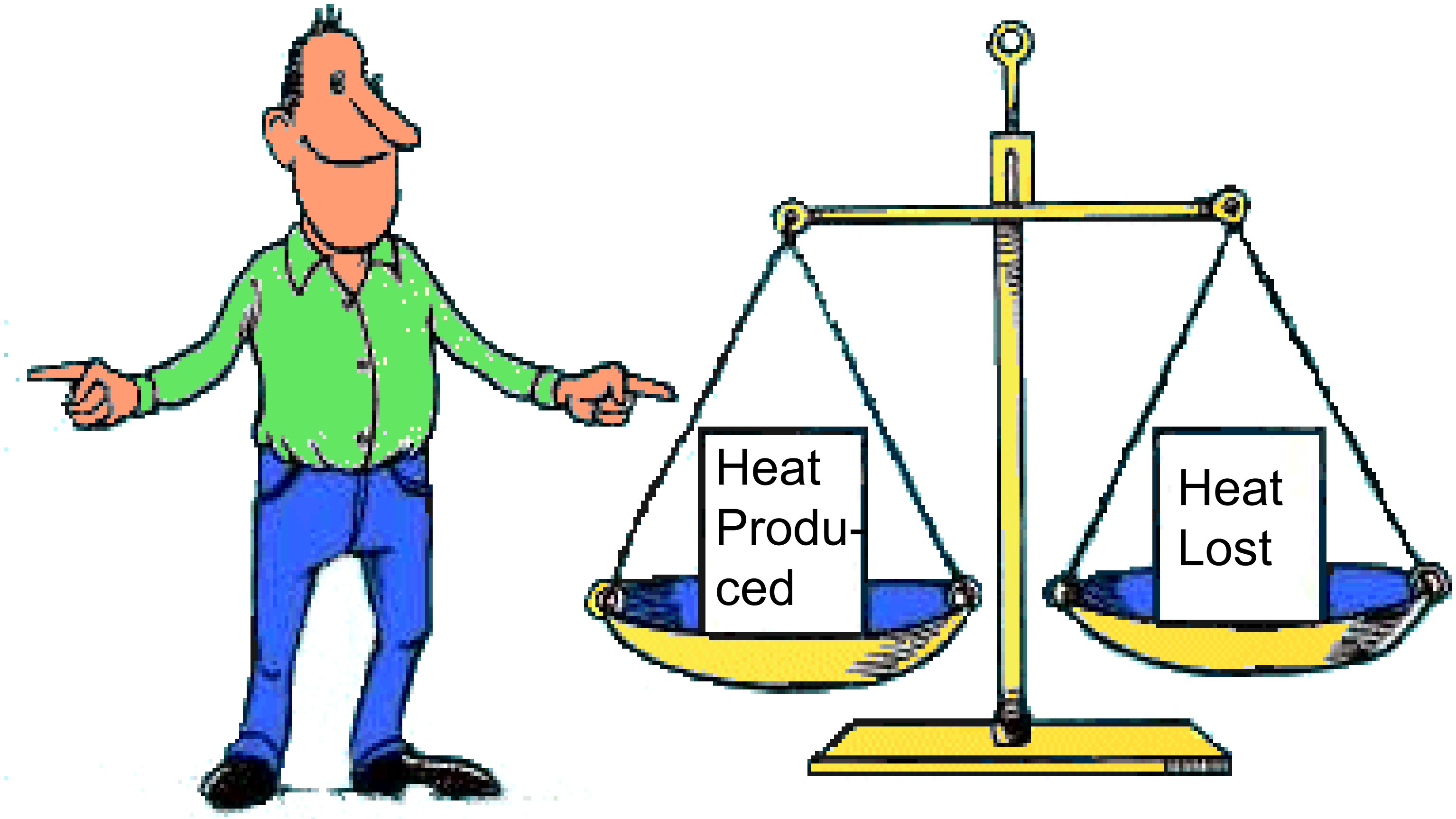
Perception of Thermal Environment



Warm impulses | Cold impulses | Activity

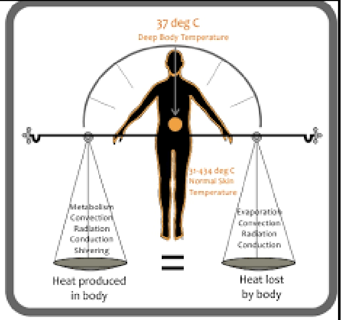
- Heat sensor in Hypothalamus send impulses when temperature exceeds 37 ºC.
- Cold sensors sends impulses when skin temperature below 34 ºC.
- The bigger temperature difference, the more impulses.
- If impulses are of same magnitude, you feel thermally neutral.
- If not, you feel cold or warm.

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

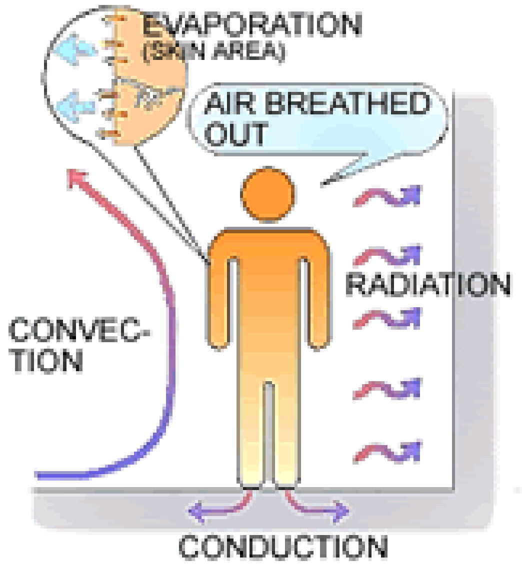
S = rate of heat storage of human body

M = metabolic rate

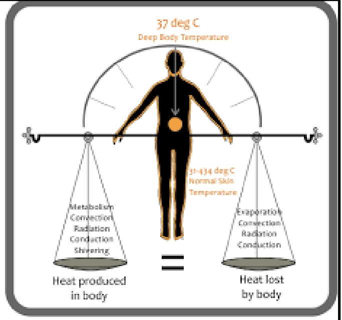
W = mechanical work done by human body

E = rate of total evaporation loss

R + C = dry heat exchange through radiation & convection



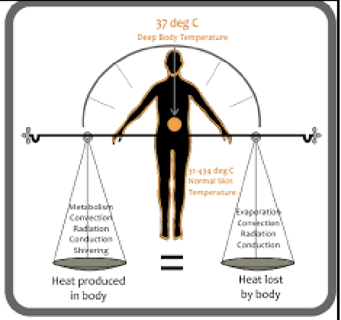
Storage = Production – Loss



Heat Balance Equation

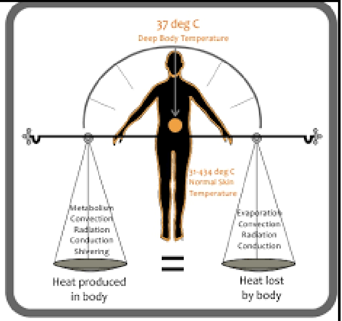
- Rate of heat storage, S
  - proportional to rate of change in mean body temp.
  - normally, S is zero; adjusted by the thermo-regulatory system of the body
- Metabolic rate, M
  - heat released from human body per unit skin area
    - depends on muscular activities, environment, body sizes, etc.; unit is “met” (= 58.2 W/m^2)
    - 1 met = seated quiet person (100 W if body surface area is 1.7 m^2); see also the table in Figure 1

Heat Balance Equation



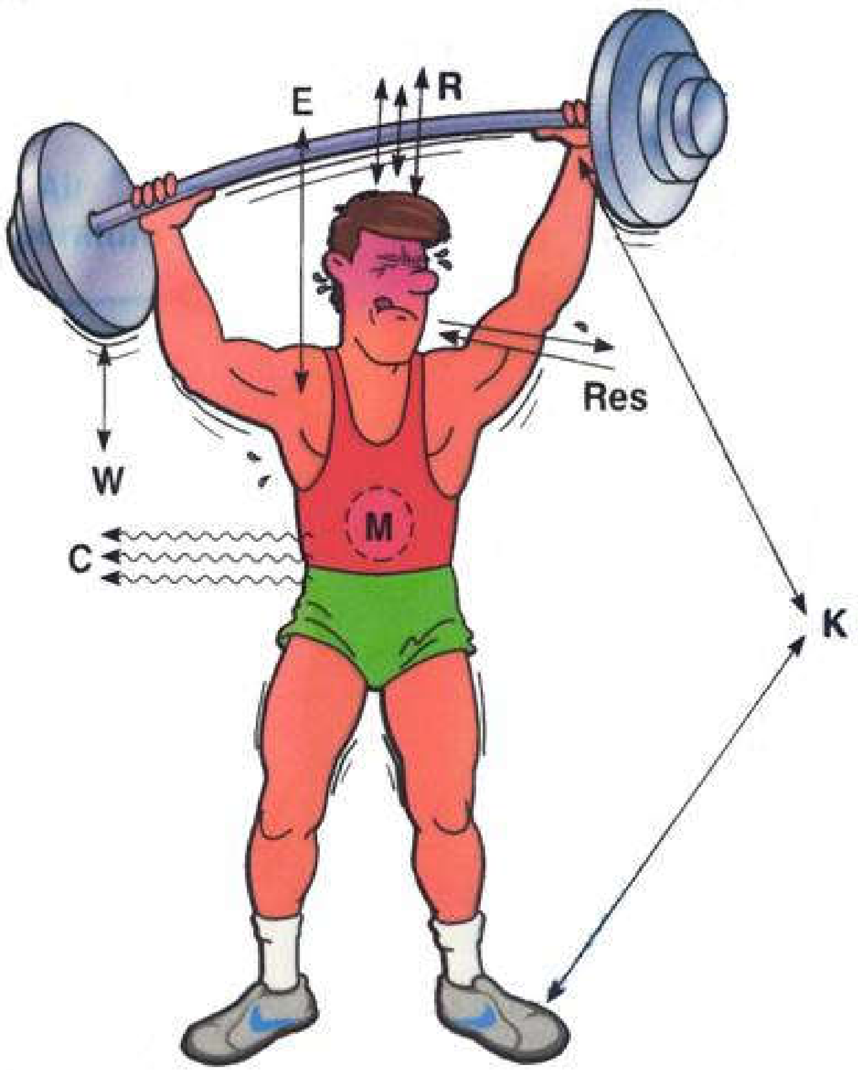
- Mechanical work, W
  - energy in human body transformed into external mechanical work
- Evaporative heat loss, E
  - release of latent heat energy from evaporation of body fluid
    - respired vapour loss, E_{res} (respiration heat losses: latent E_{rel} and sensible E_{rec})
    - evaporative heat loss from skin E_{sk} (include skin diffusion E_{dif} and regulatory sweating E_{rsw})

Heat Balance Equation



- Dry heat exchange, R + C
  - through convective and radiative heat transfer
    - heat loss by radiation if skin temp. > temp. of surrounding surfaces
    - heat loss by convection if skin temp. > dry bulb temp.
  - **mean radiant temperature** (t_r) is that uniform temp. of an imaginary black enclosure which result in the same heat loss by radiation as the actual enclosure

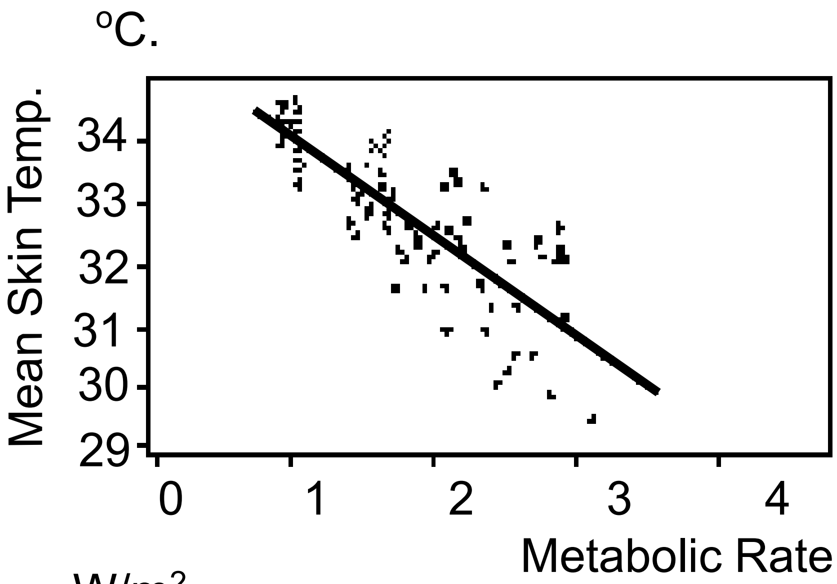
The Energy Balance

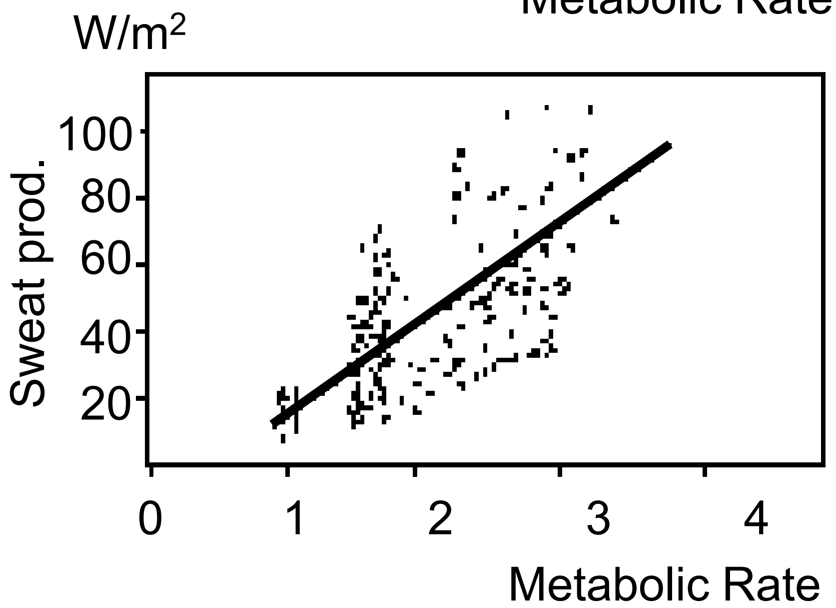


- The dry heat loss (R+C) represents ~70% at low Clo-values and ~60% at higher Clo-values
- Conduction (K) is normally insignificant compared to the total heat exchange

- Parameters influencing the Heat Loss from a person

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)

Prediction 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)

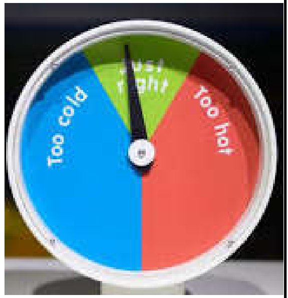
V = air velocity (m/s)

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

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

P_s = water vapour pressure (kPa)

Prediction of Thermal Comfort



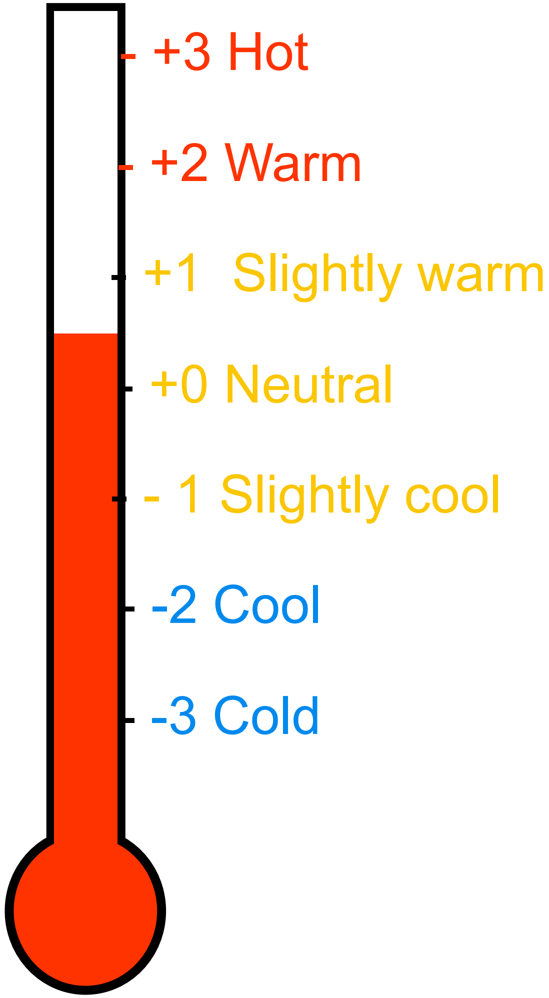
- Fanger's equation is complex
  - but it may be transformed to comfort diagrams
  - it can also be used to yield three indices:
    - predicted mean vote (PMV)
    - predicted percentage of dissatisfied (PPD)
    - lowest possible percentage dissatisfied (LPPD)

(See also: Thermal comfort - Wikipedia http://en.wikipedia.org/wiki/Thermal_comfort)

Prediction of Thermal Comfort

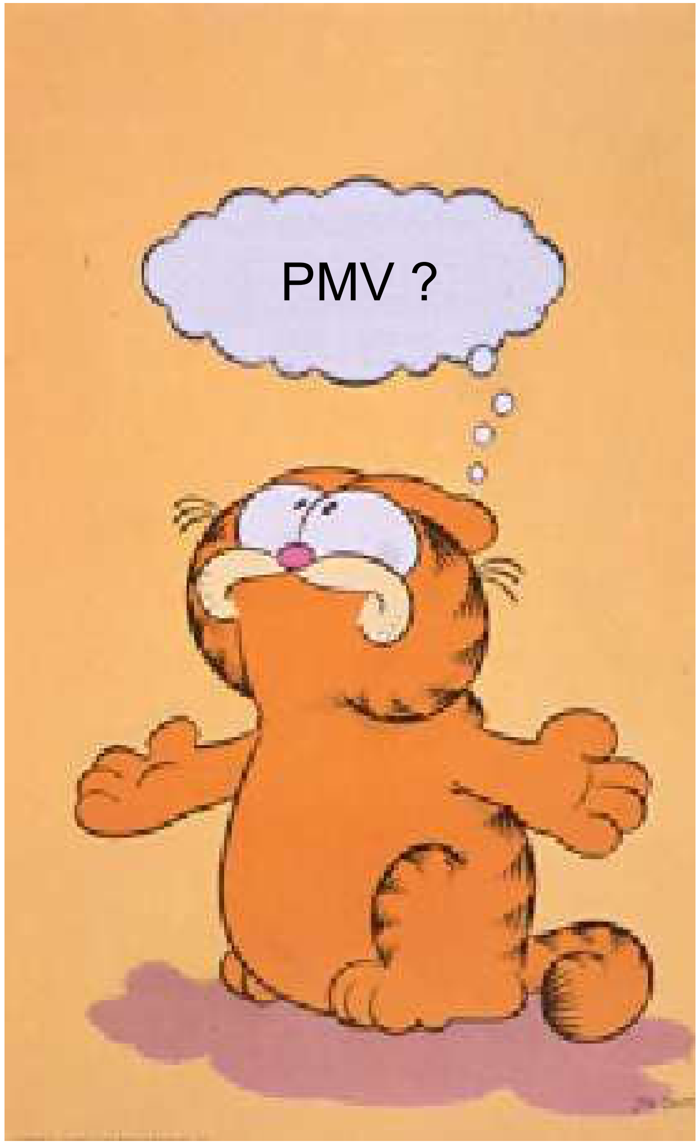
- **PMV**
  - a complex function of six major comfort parameters;
  - predict mean value of the subjective ratings of a group of people in a given environment
- **PPD**
  - determined from PMV as a quantitative measure of thermal comfort
  - 'dissatisfied' means not voting -1, +1 or 0 in PMV
  - normally, 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



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

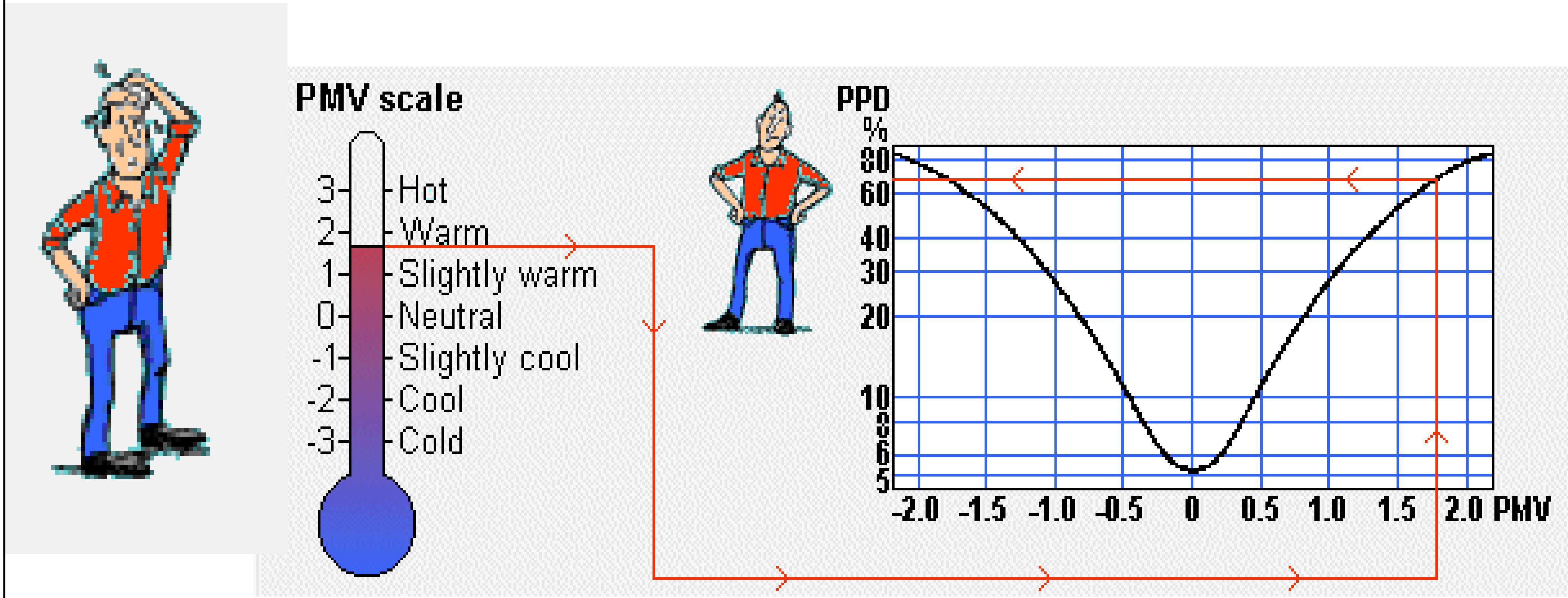
$$\Longrightarrow$$

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

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

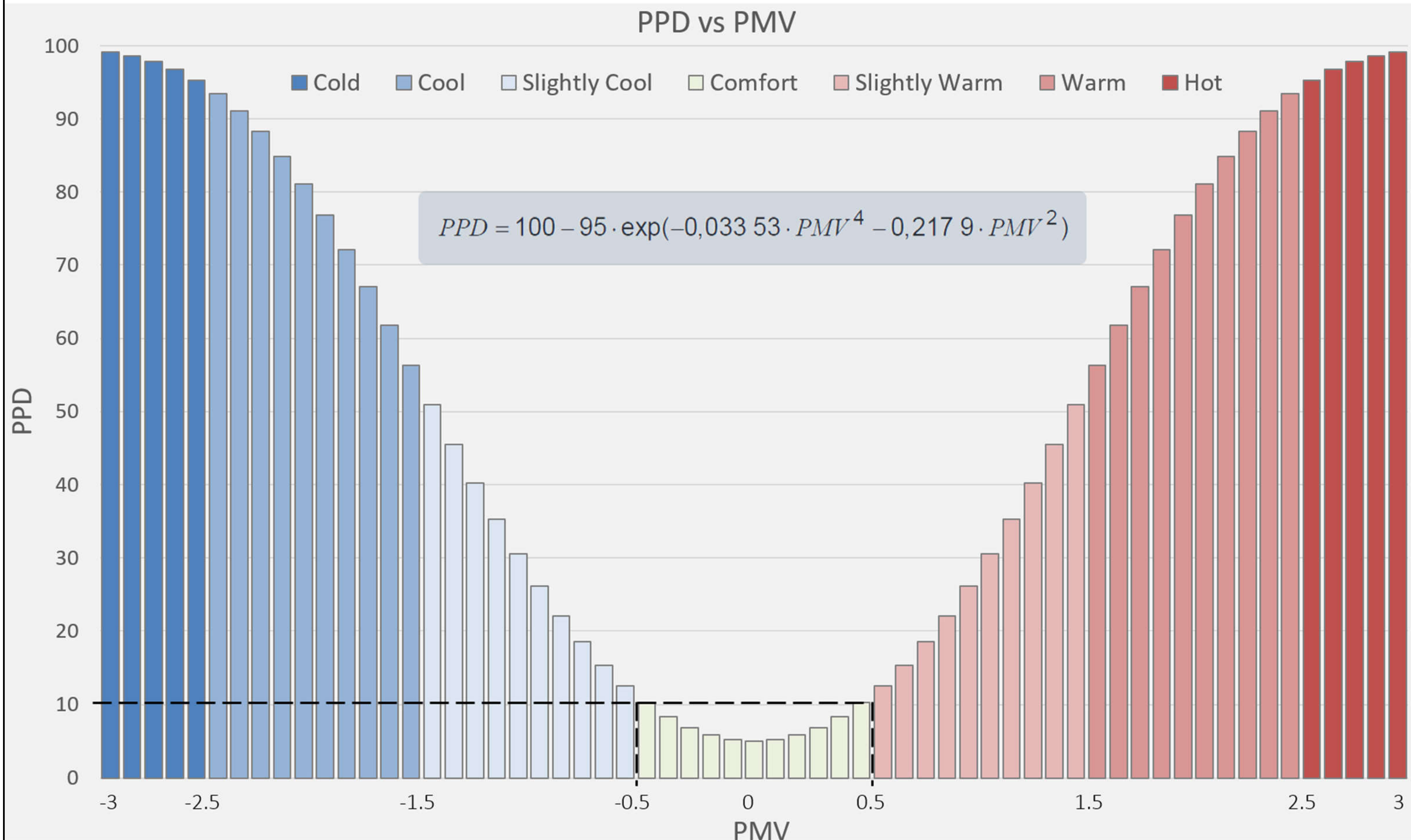
M [MET)] Icl [CLO]

PMV and PPD



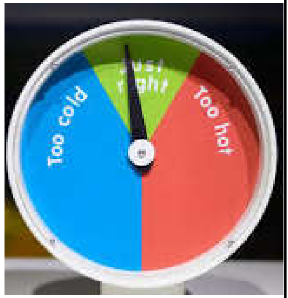
- PMV-index (Predicted Mean Vote) predicts the subjective ratings of the environment in a group of people.
  - 0 = neutral (still 5% people are dissatisfied)
- PPD-index predicts the number of dissatisfied people.

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



(Source: https://www.linkedin.com/pulse/role-cfd-evaluating-occupant-thermal-comfort-sandip-jadhav/)

Prediction 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 $^oC \leq$ SET $\leq$ 26.1 ^oC
    - for winter, 20.0 $^oC \leq$ SET $\leq$ 23.9 ^oC

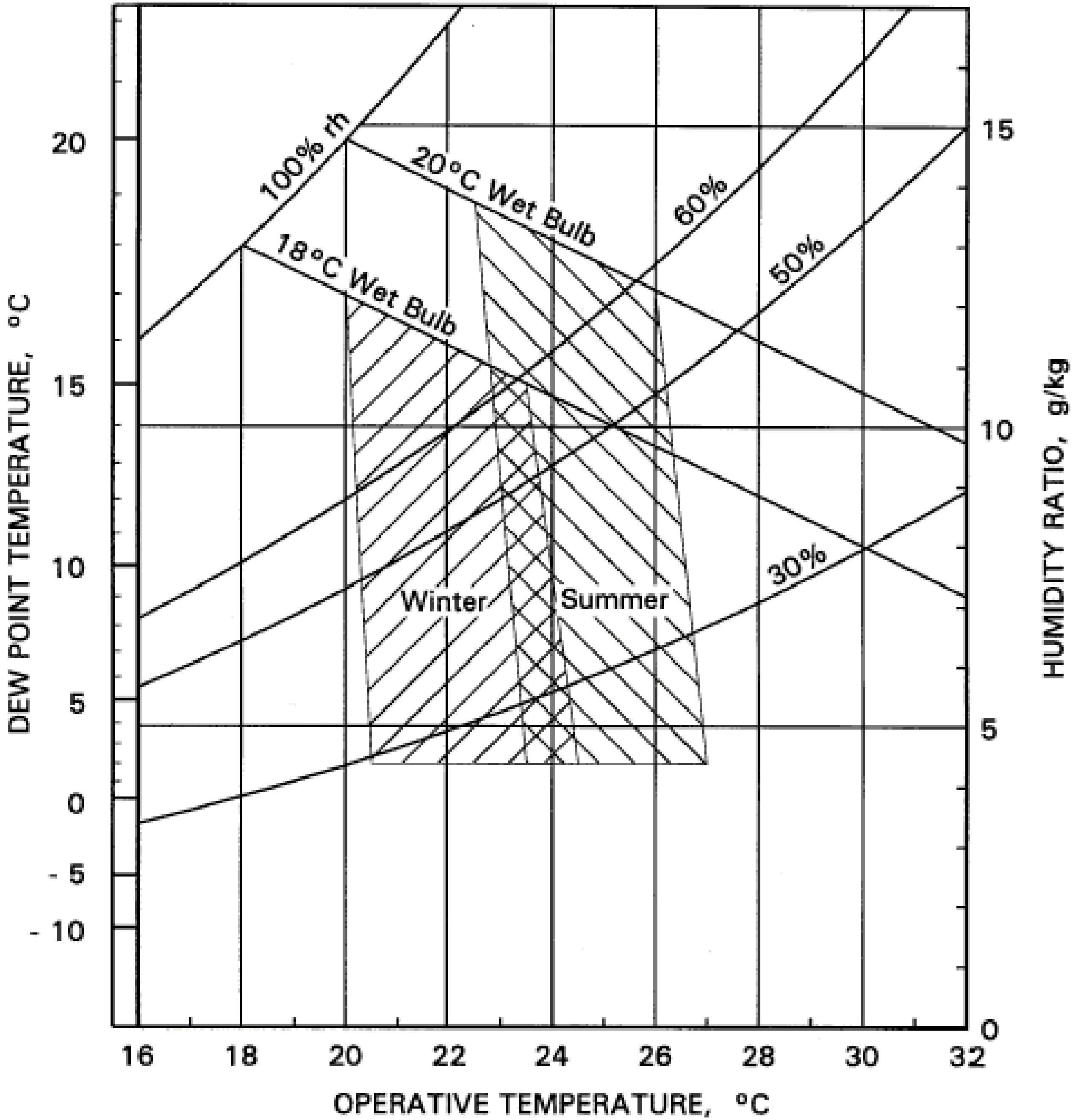
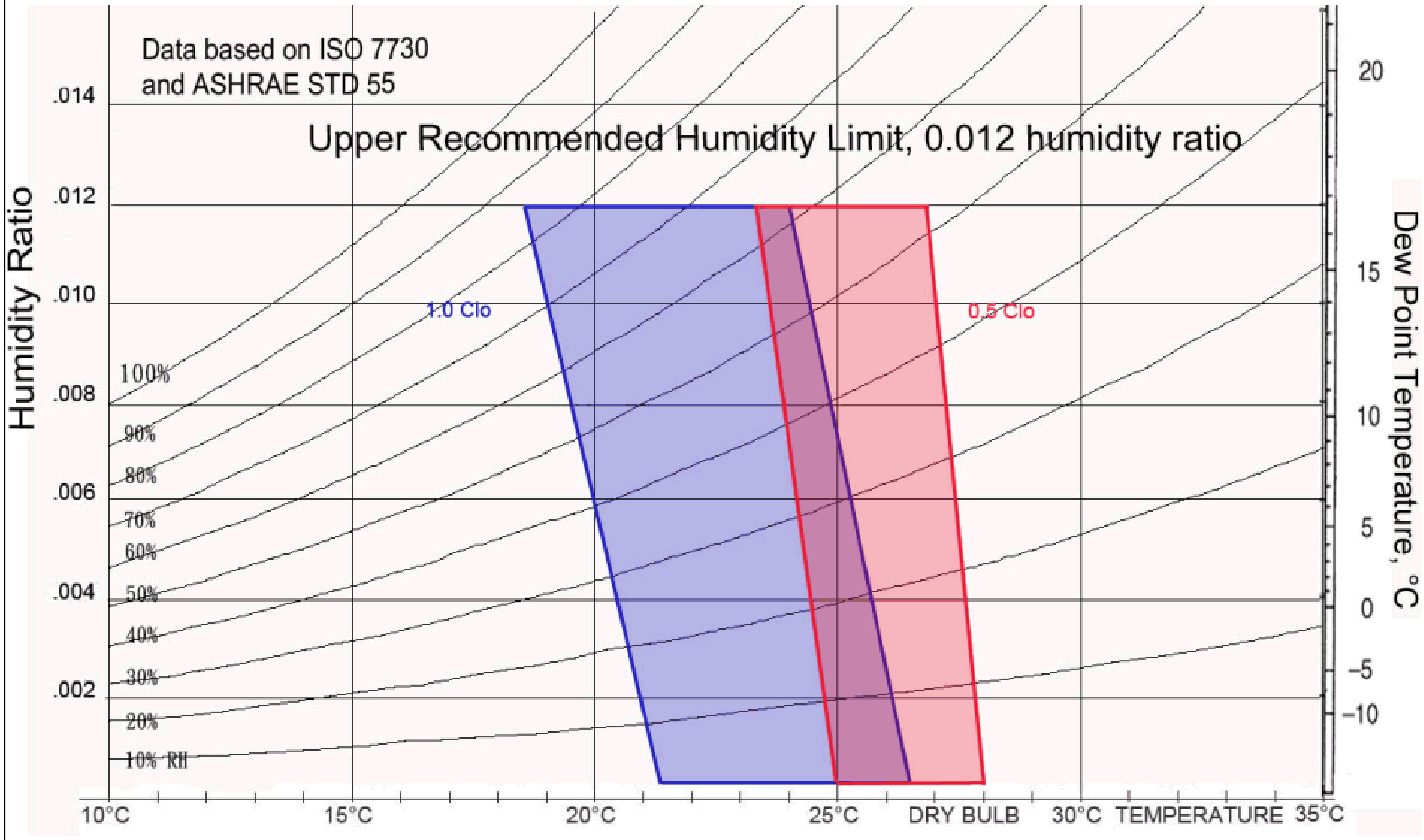


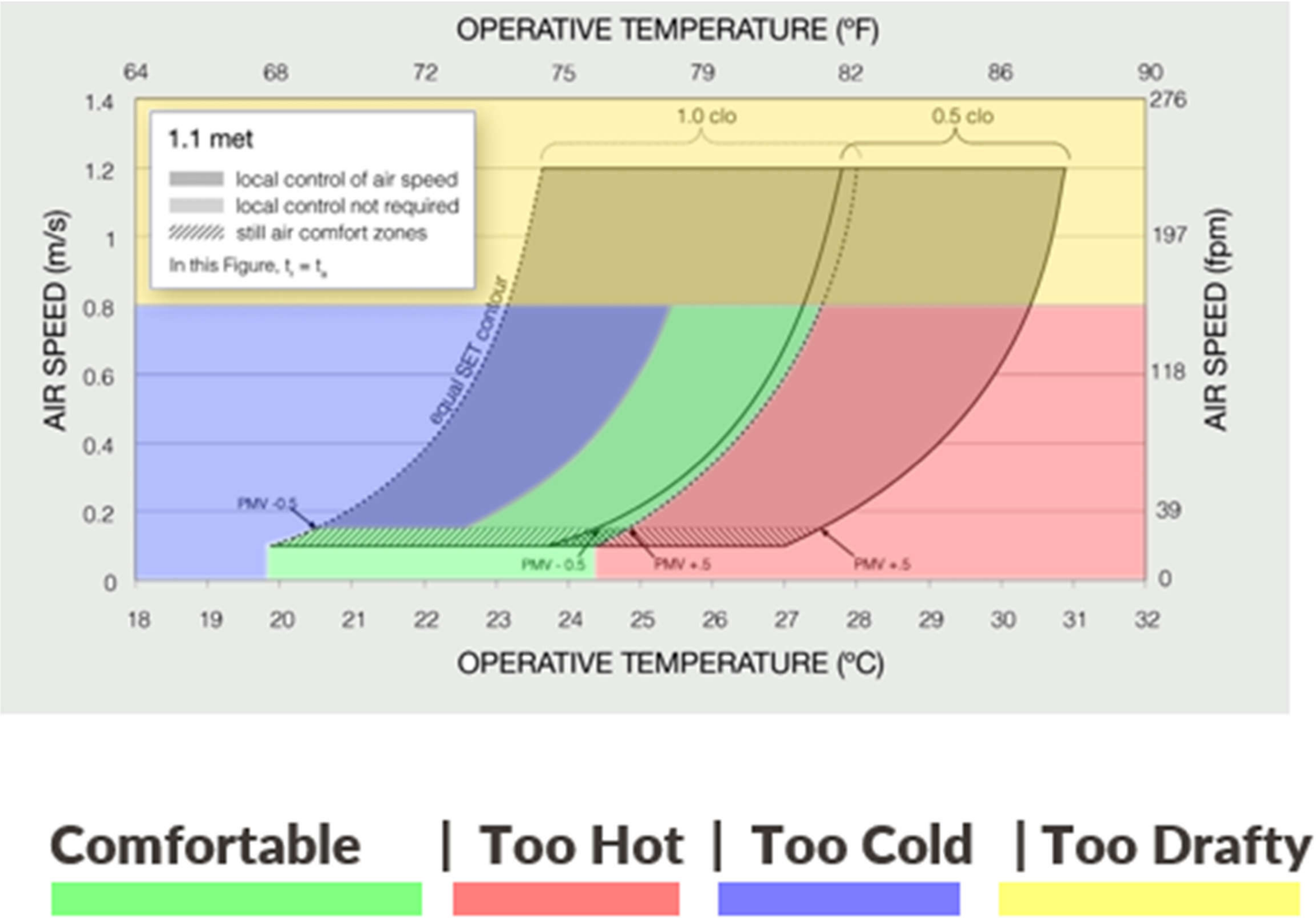
Fig. 5 ASHRAE Summer and Winter Comfort Zones

(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)

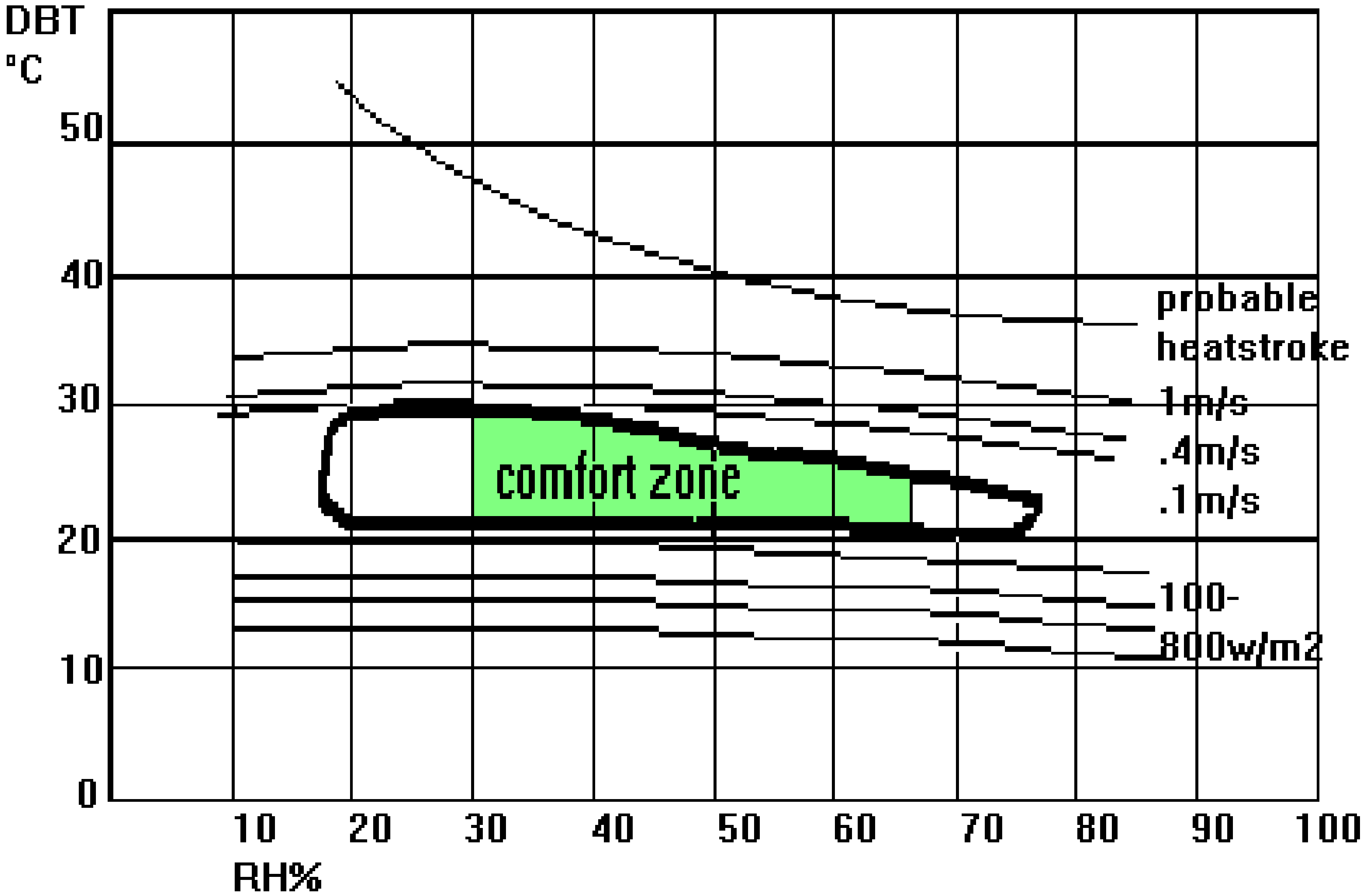


Thermal comfort chart using ASHRAE 55 parameters

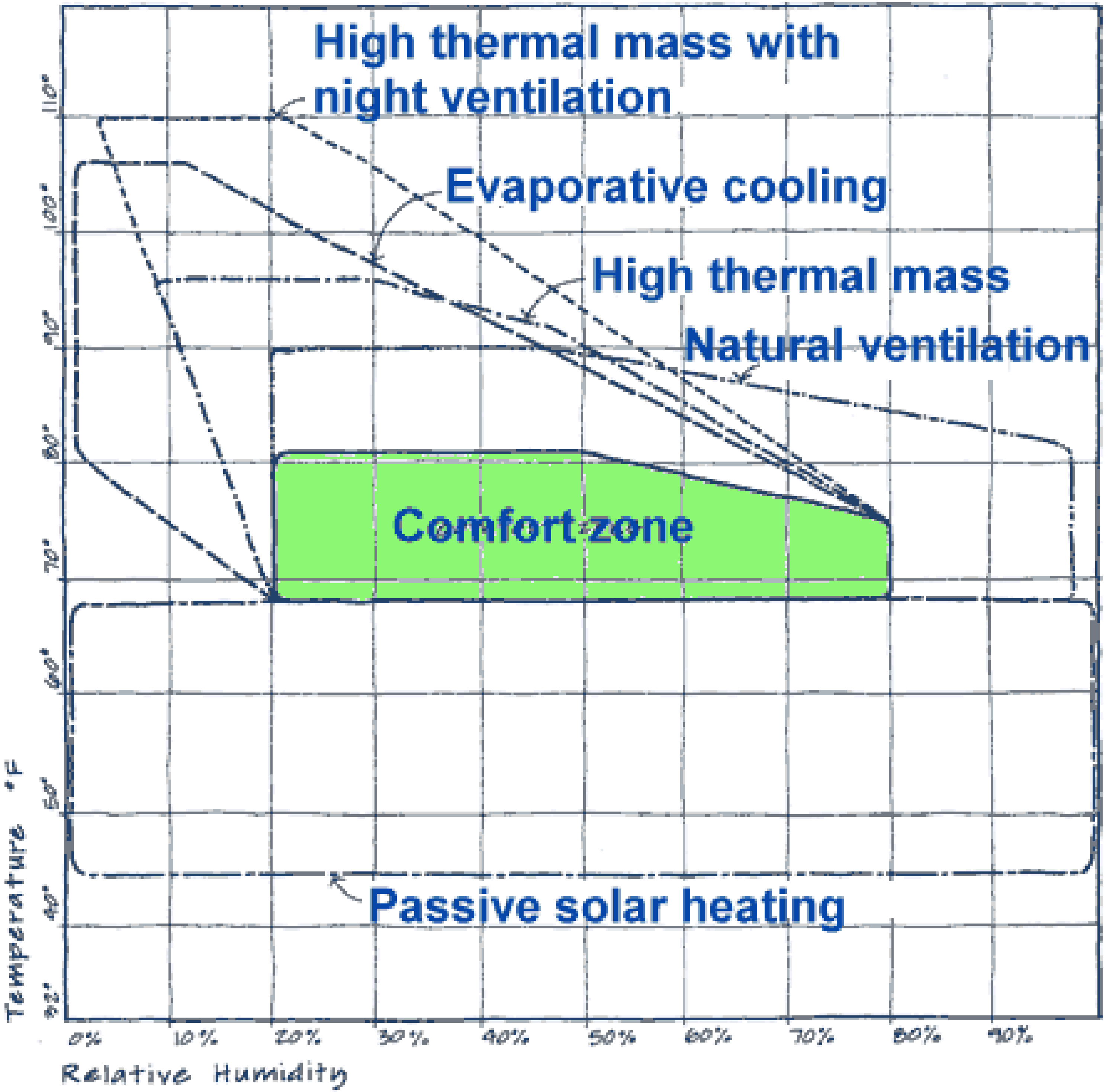


(Source: https://www.simscale.com/blog/2019/08/what-is-ashrae-55-thermal-comfort/)

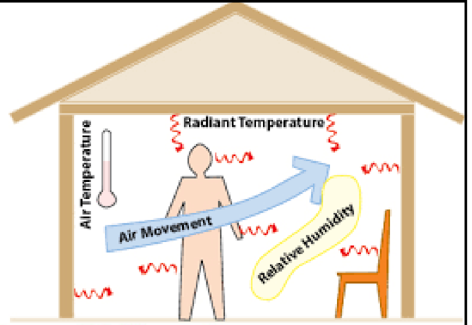
Olgyays bioclimatic chart



Bioclimatic chart with design strategies

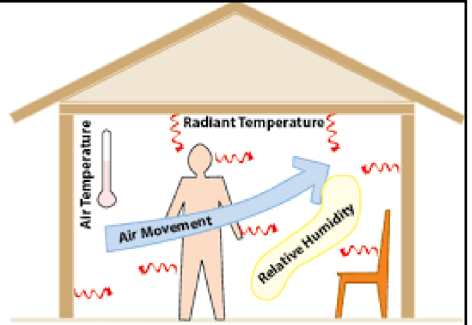


Influencing Factors



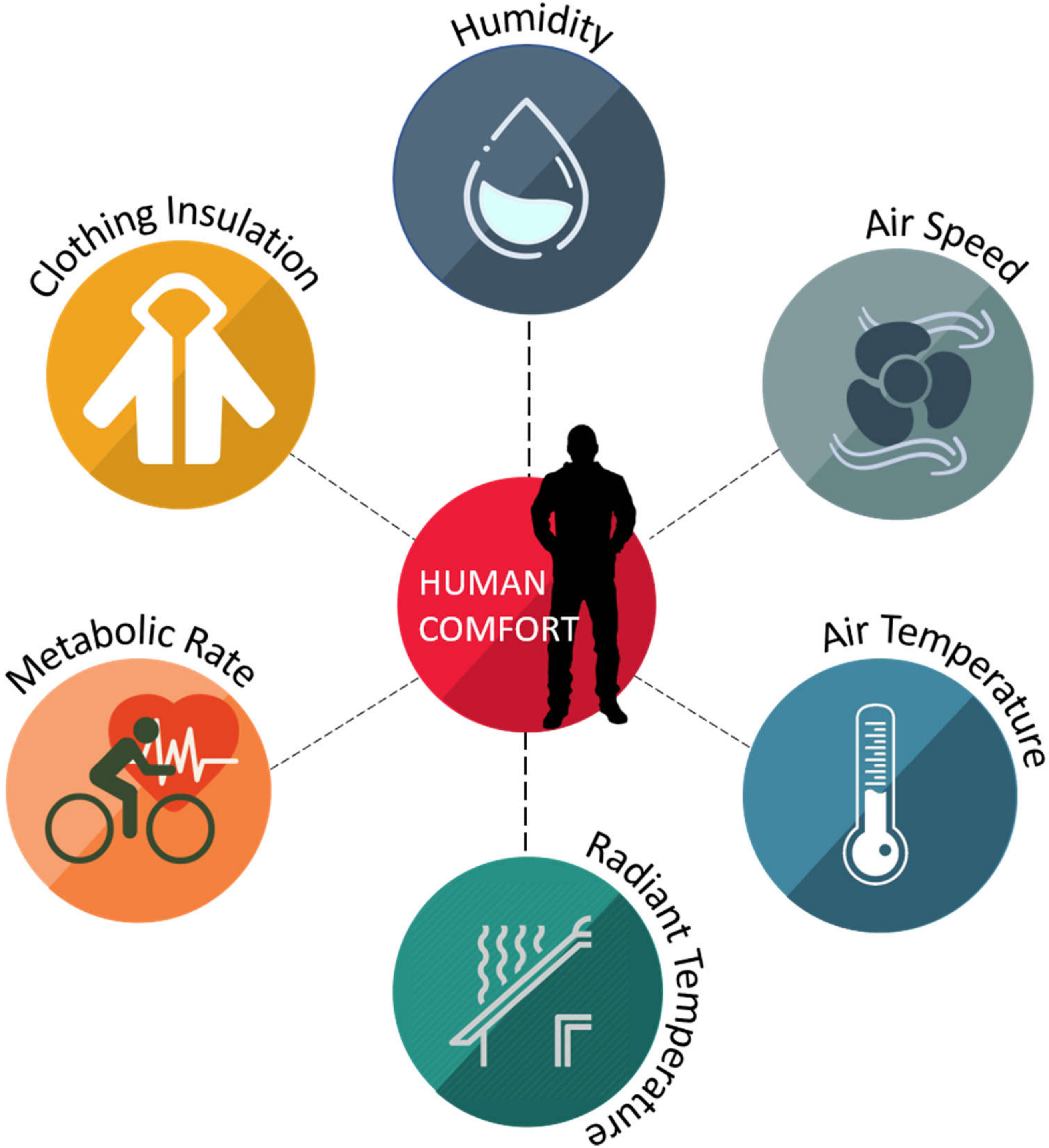
- Environmental factors:
  - Dry-bulb temperature (or air temperature)
  - Relative humidity (or water vapour pressure)
    - Influences evap. heat loss and skin wettedness
    - Usually RH between 30% and 70% is comfortable
  - Air velocity (increase convective heat loss)
    - Preferable air velocity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

Influencing Factors



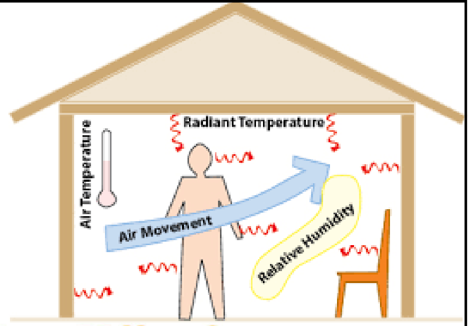
- Other factors affecting comfort:
  - Age
    - Sensation of old people and younger people
  - Adaptation
    - People in warm climates may adapt to hot environment
  - Sex
    - Women: lower skin temp., evap loss & lower met. rate
    - Clothing and perferrence of temp.

Environmental and personal factors that influence thermal comfort



(Source: https://www.linkedin.com/pulse/role-cfd-evaluating-occupant-thermal-comfort-sandip-jadhav/)

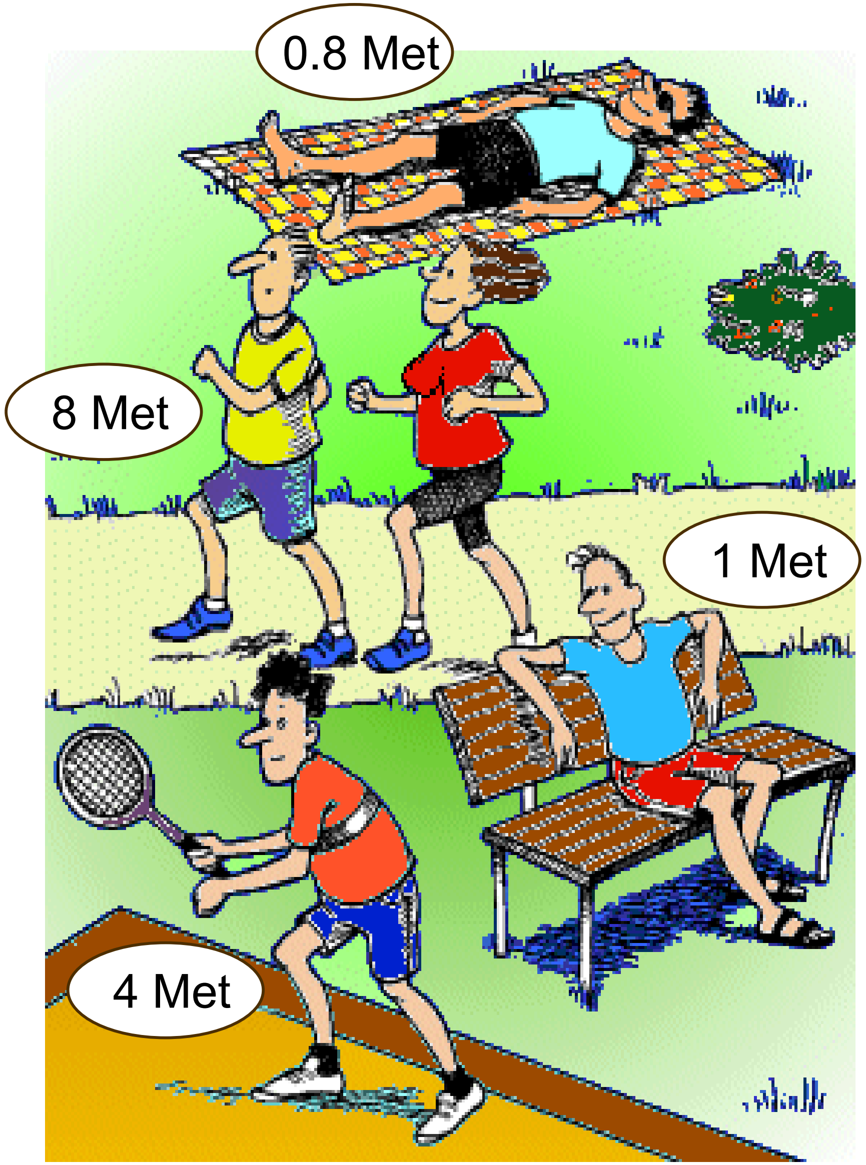
Influencing Factors



- What should be estimated?
- Parameters to estimate and calculate are:

Met	Estimation of Metabolic rate
Clo	Calculation of Clo-value

Metabolic Rate

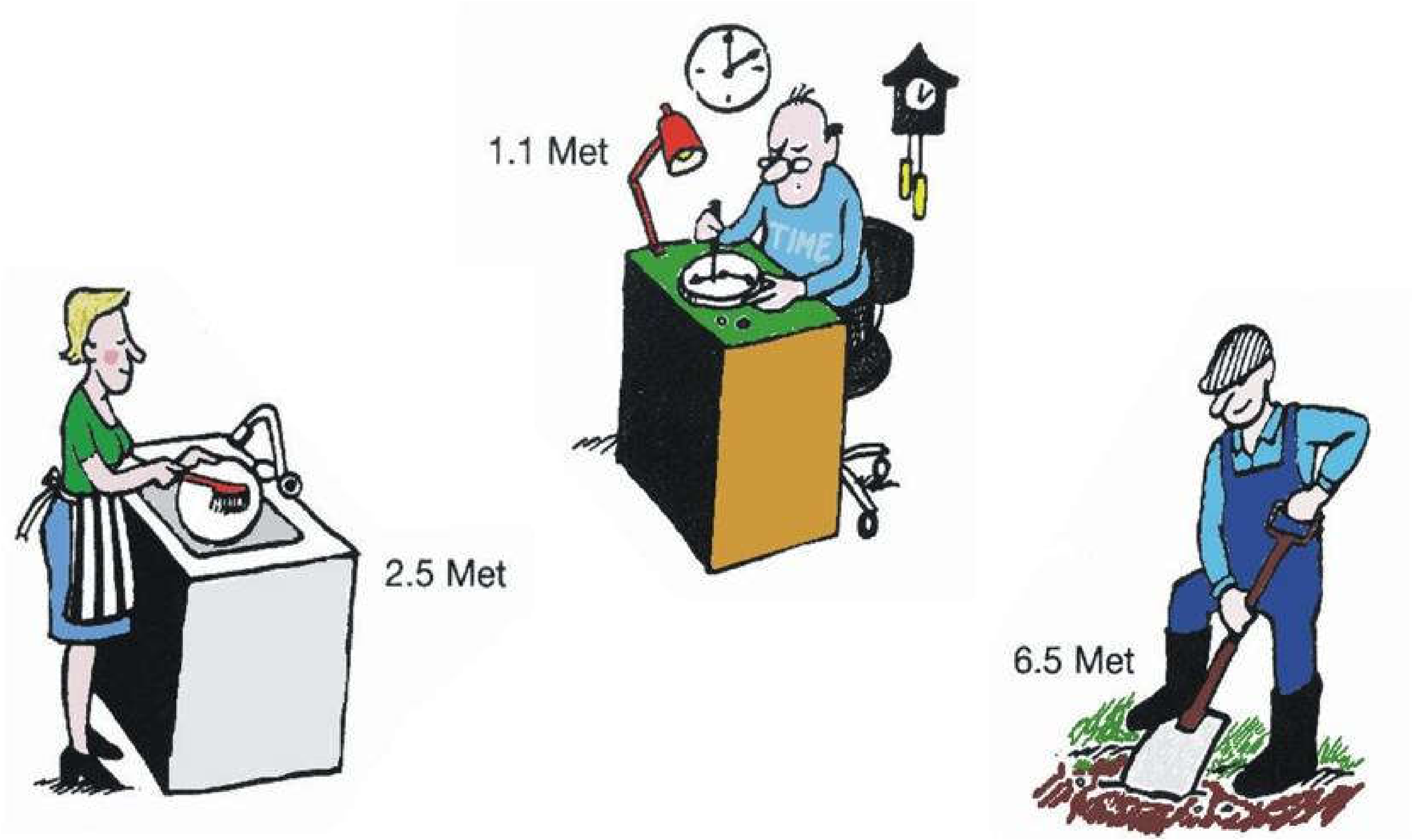


- Energy released by metabolism depends on muscular activity.
- Metabolism is measured in Met (1 Met=58.15 W/m^2 body surface).
- Body surface for normal adult is 1.7 m^2.
- A sitting person in thermal comfort will have a heat loss of 100 W.
- Average activity level for the last hour should be used when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

Met Value Table

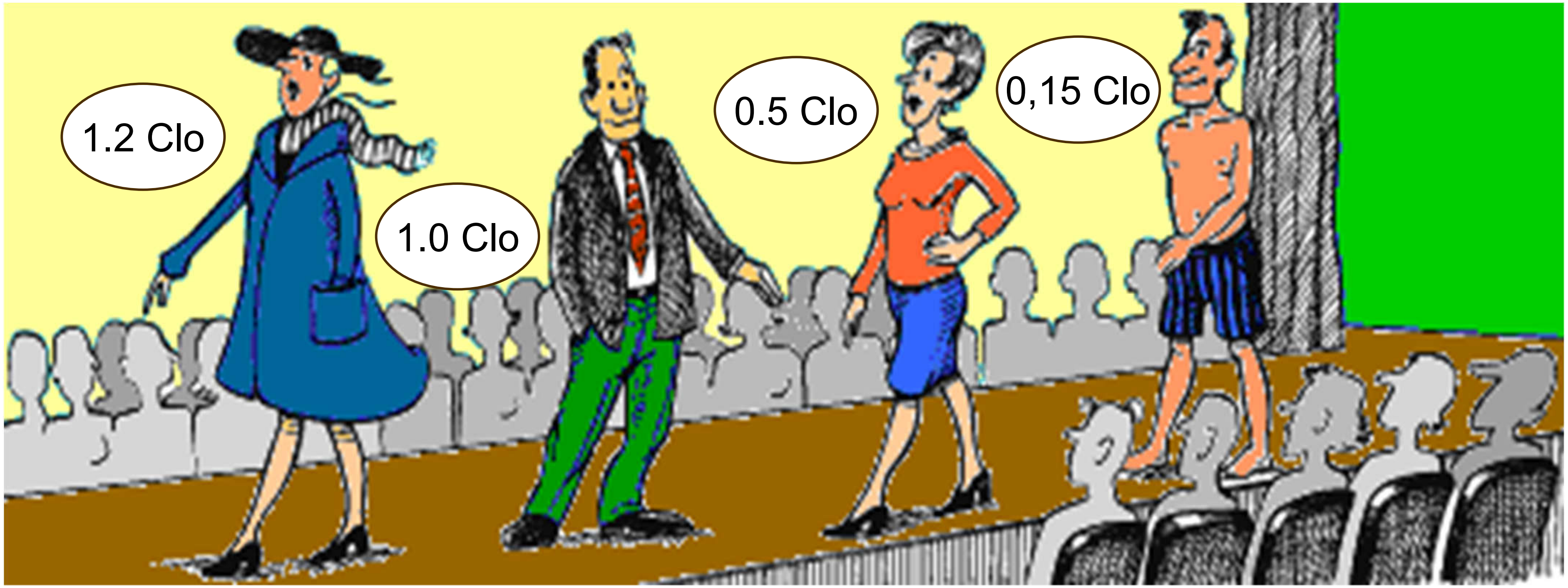
Activity	Metabolic rates [M]	
Reclining	46 W/m^2	0.8 Met
Seated relaxed	58 W/m^2	1.0 Met
Clock and watch repairer	65 W/m^2	1.1 Met
Standing relaxed	70 W/m^2	1.2 Met
Car driving	80 W/m^2	1.4 Met
Standing, light activity (shopping)	93 W/m^2	1.6 Met
Walking on the level, 2 km/h	110 W/m^2	1.9 Met
Standing, 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



Met Value Examples

Calculation of Insulation in Clothing



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

Clo Values Table

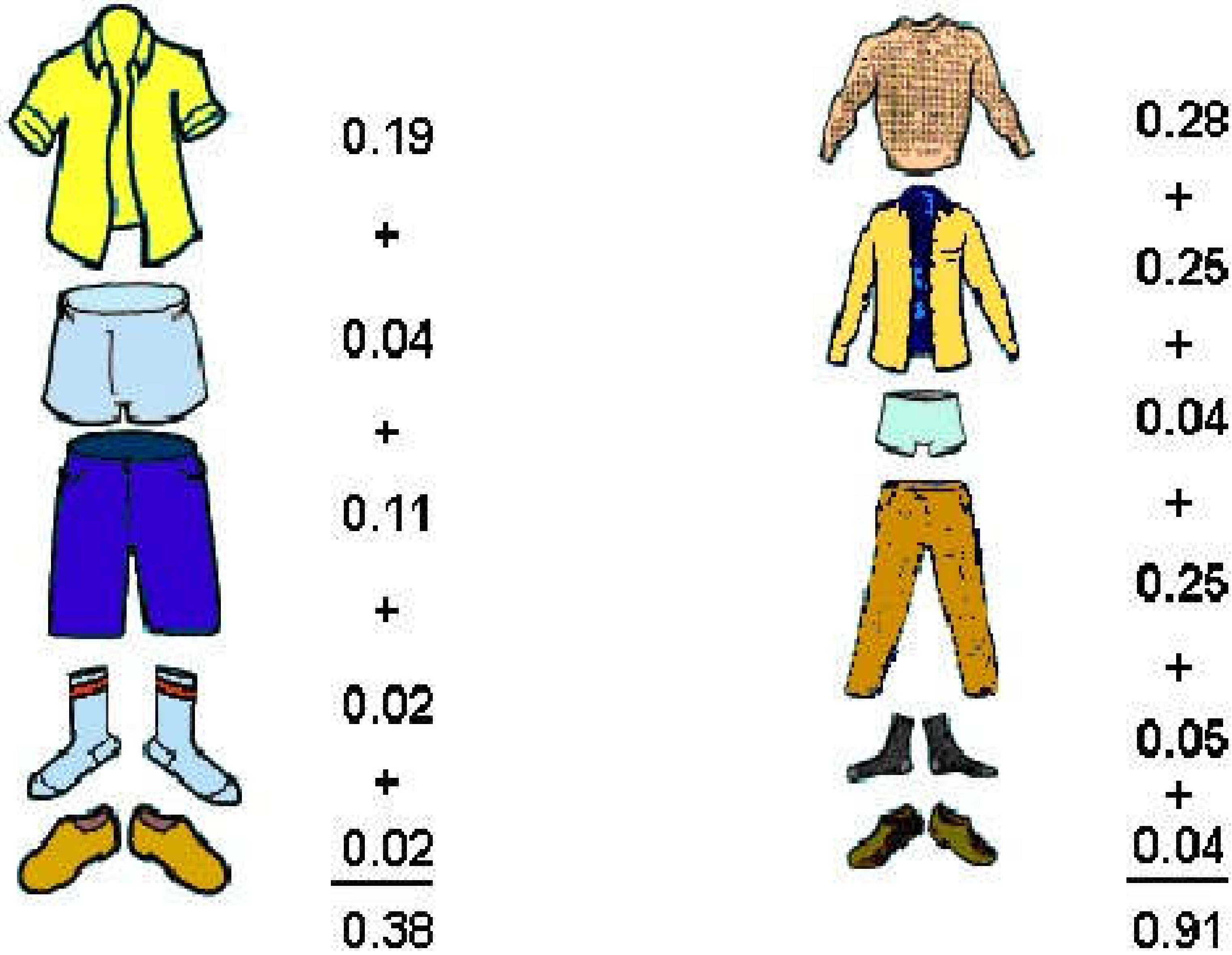
Garment description		I_{clu} Clo	I_{clu} m^2 °C/W
Underwear	Pantyhose	0.02	0.003
	Briefs	0.04	0.006
	Pants long legs	0.10	0.016
Underwear, shirts	Bra	0.01	0.002
	T-shirt	0.09	0.014
	Half-slip, nylon	0.14	0.022
Shirts	Tube top	0.06	0.009
	Short sleeves	0.09	0.029
	Normal, long sleeves	0.25	0.039
Trousers	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 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: $I_{cl} = \sum I_{clu}$

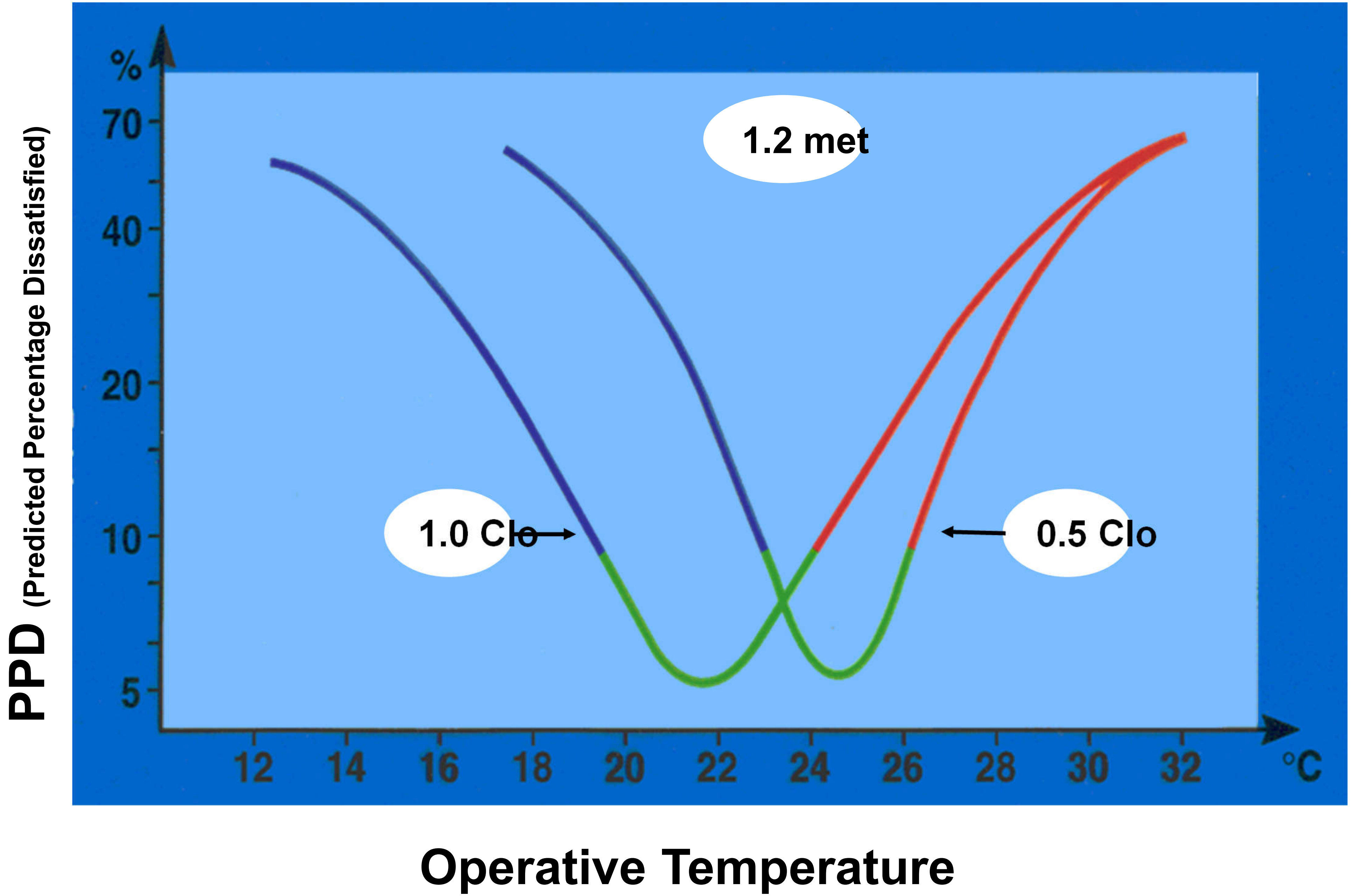


Things to consider when calculation the CLO value

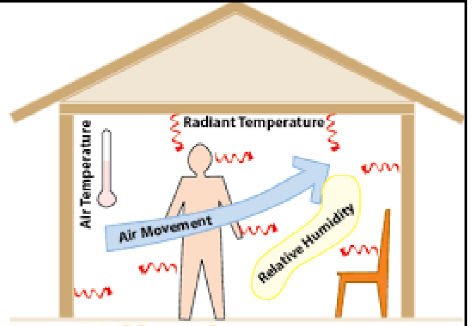
Thermal insulation of chairs

Insulation of wet clothing

Adjustment of Clo Value

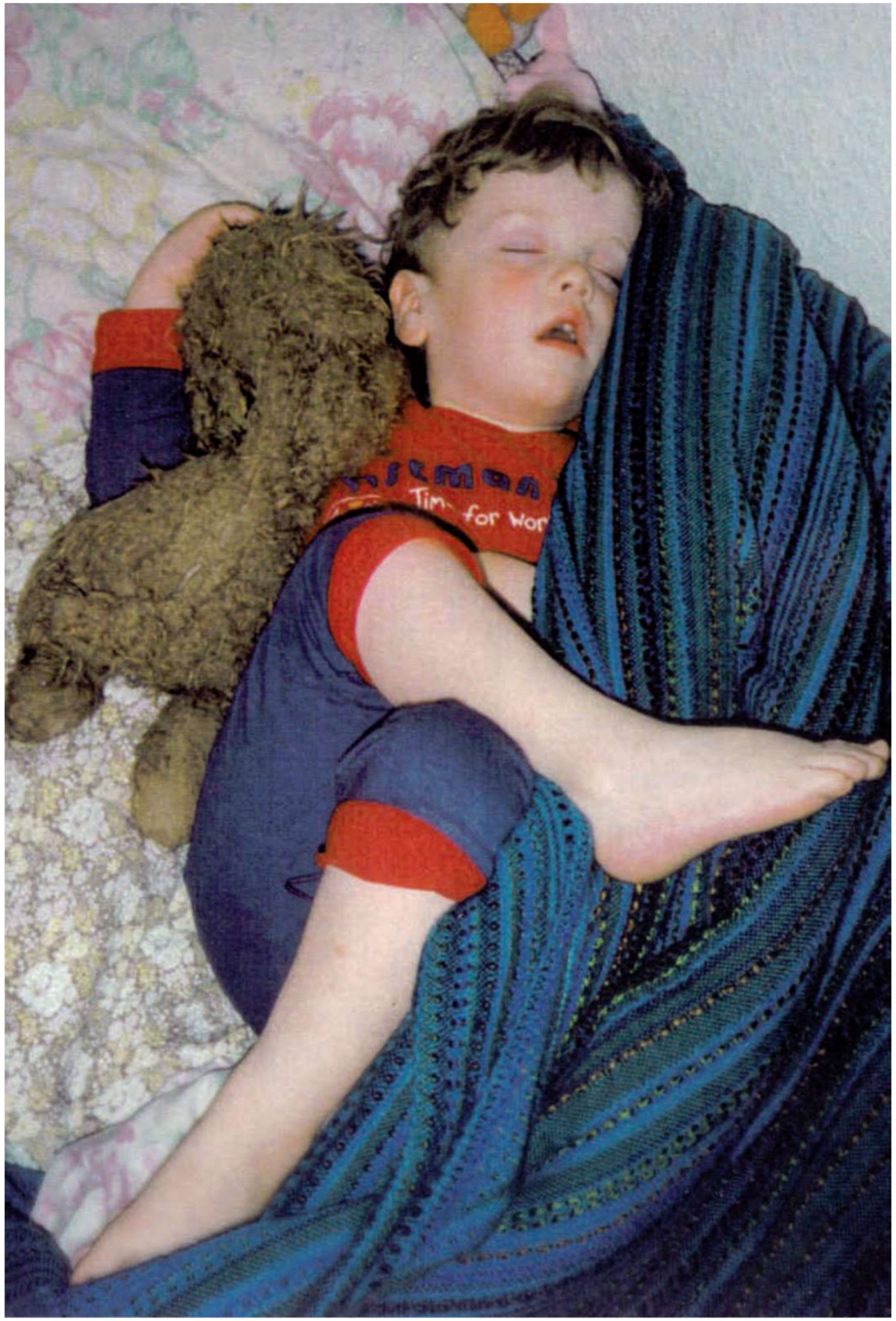


Influencing Factors



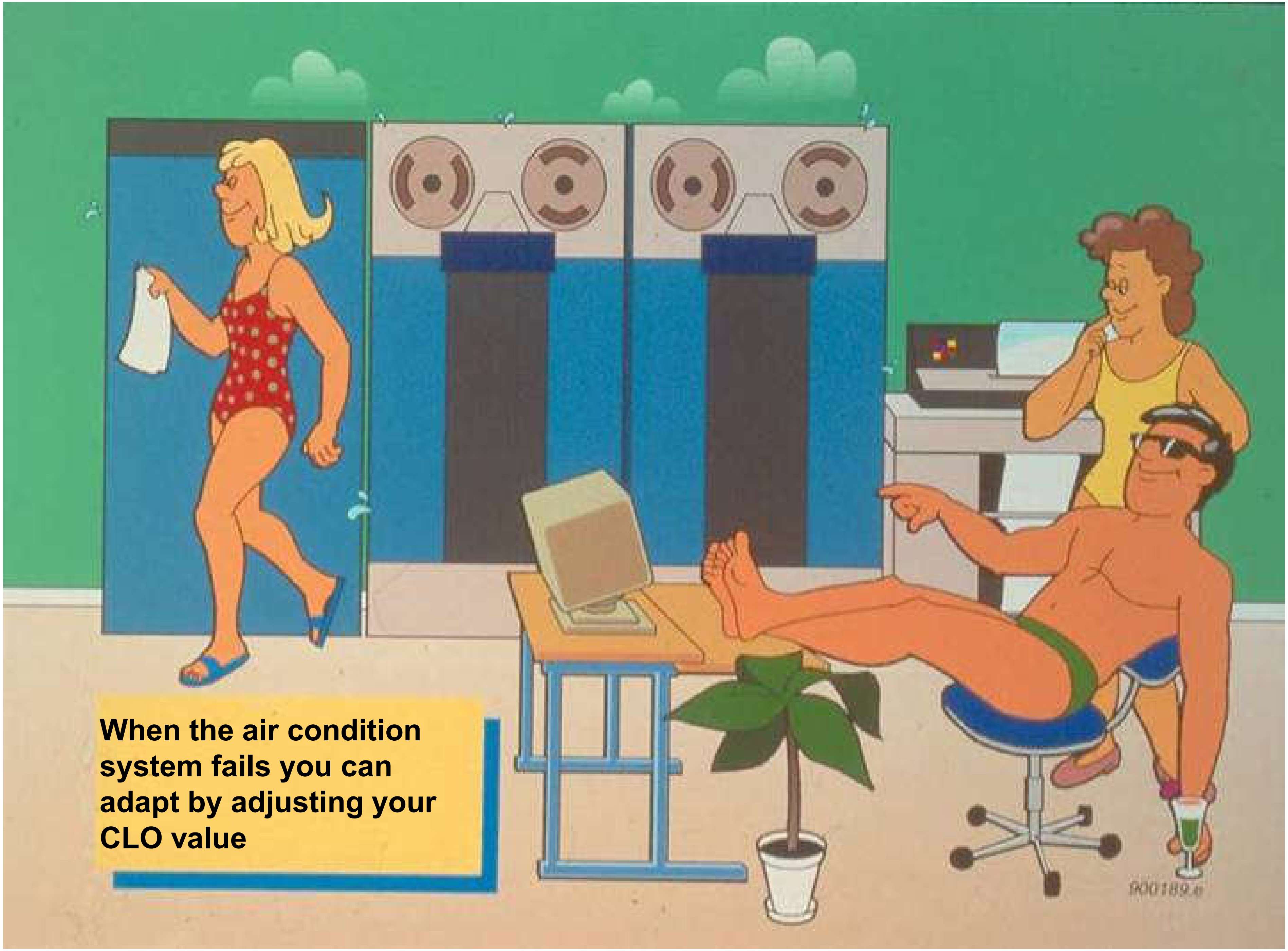
- Adaptive thermal comfort
  - People expect different thermal experiences in summer and winter, and modify behaviour accordingly
  - Comfort temperature can vary with changing outdoor conditions (esp. for natural ventilation)
    - Can reduce the average indoor–outdoor temperature difference, and consequently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

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

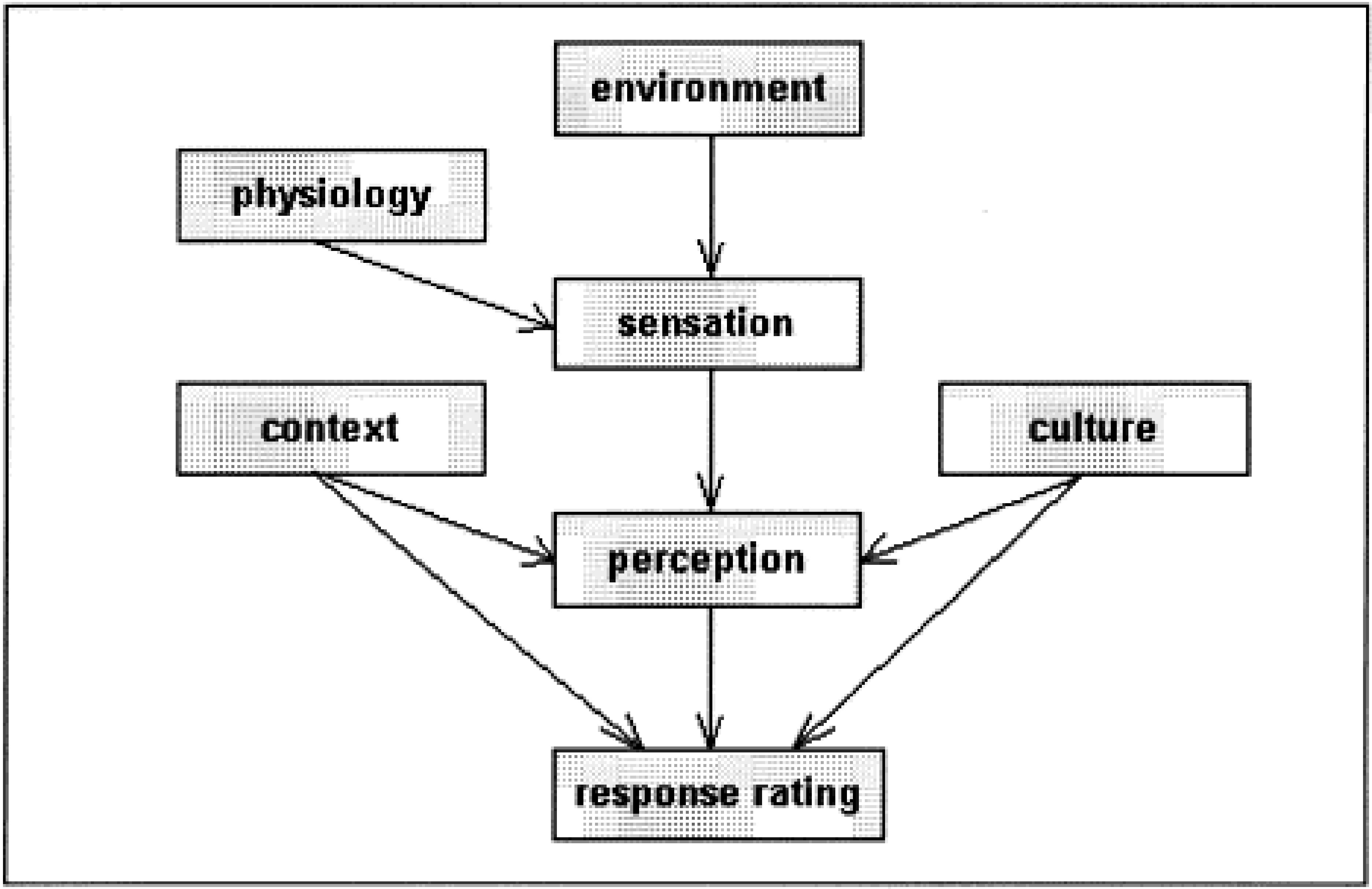


(Source: Nicol, F., Humphreys, M. and Roaf, S., 2012. *Adaptive Thermal Comfort: Principles and Practice*)

Acclimatisation/Adaptation!

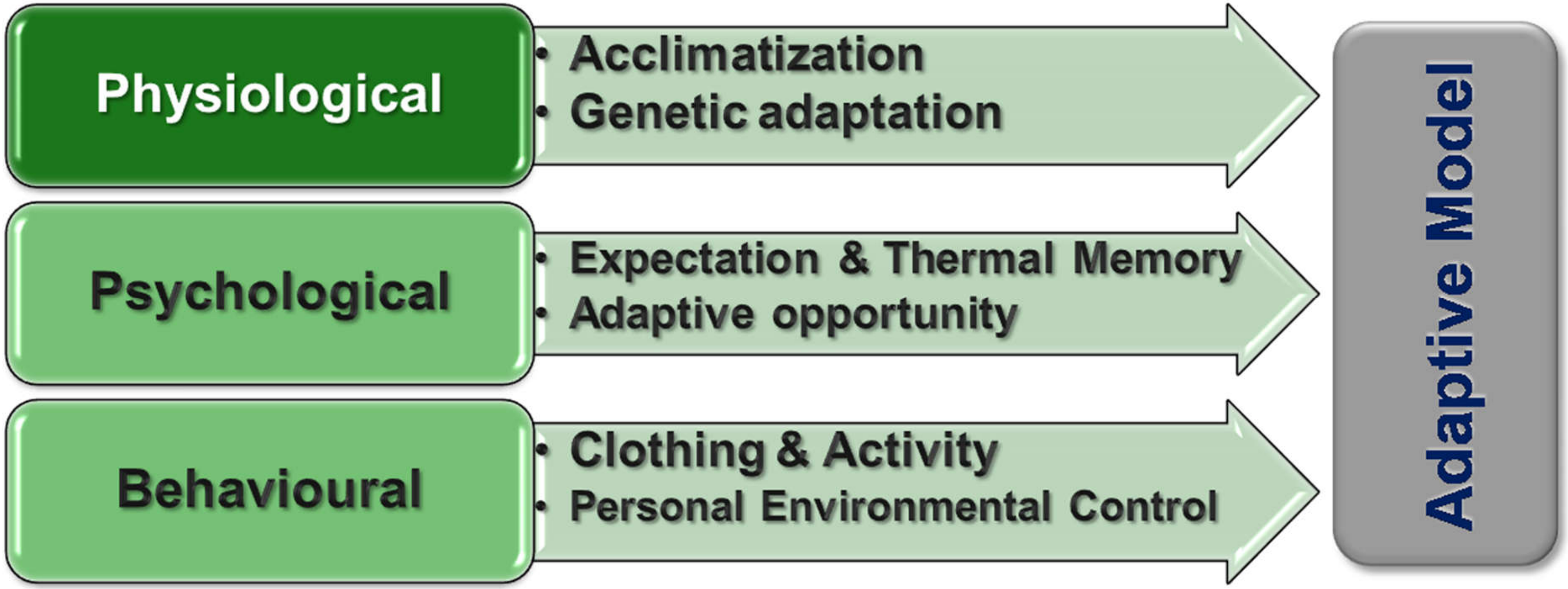


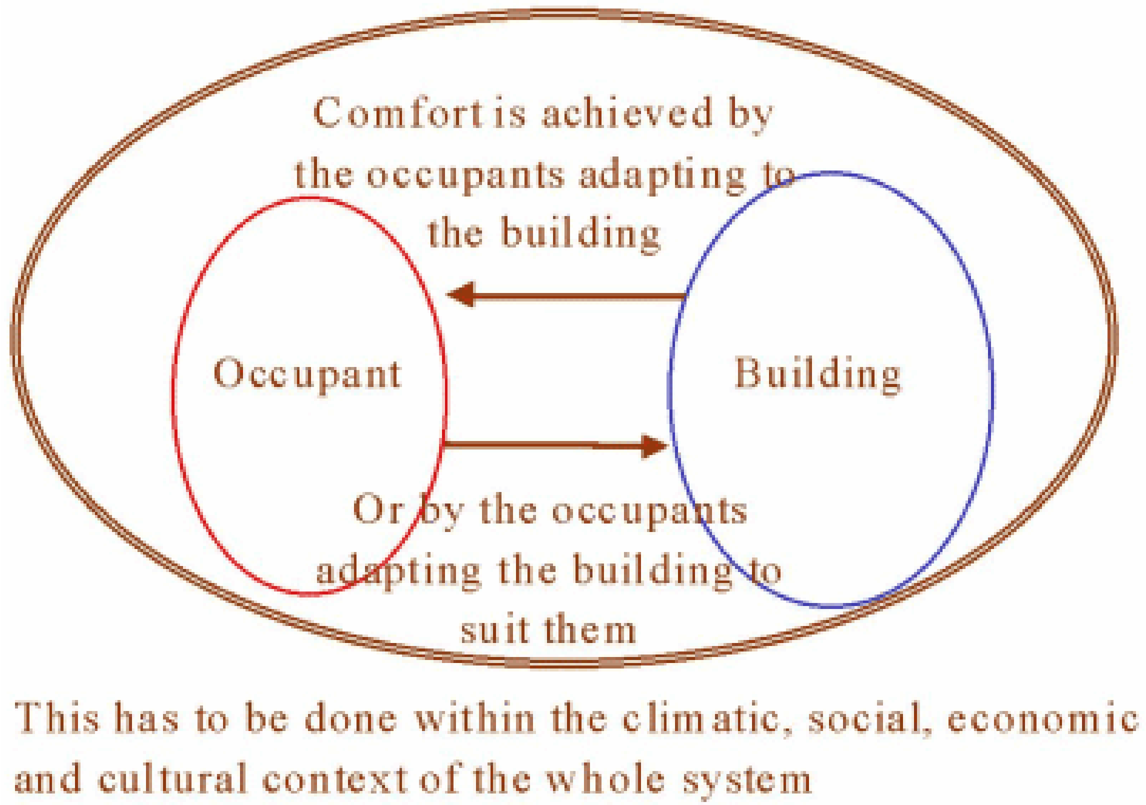
The adaptation model



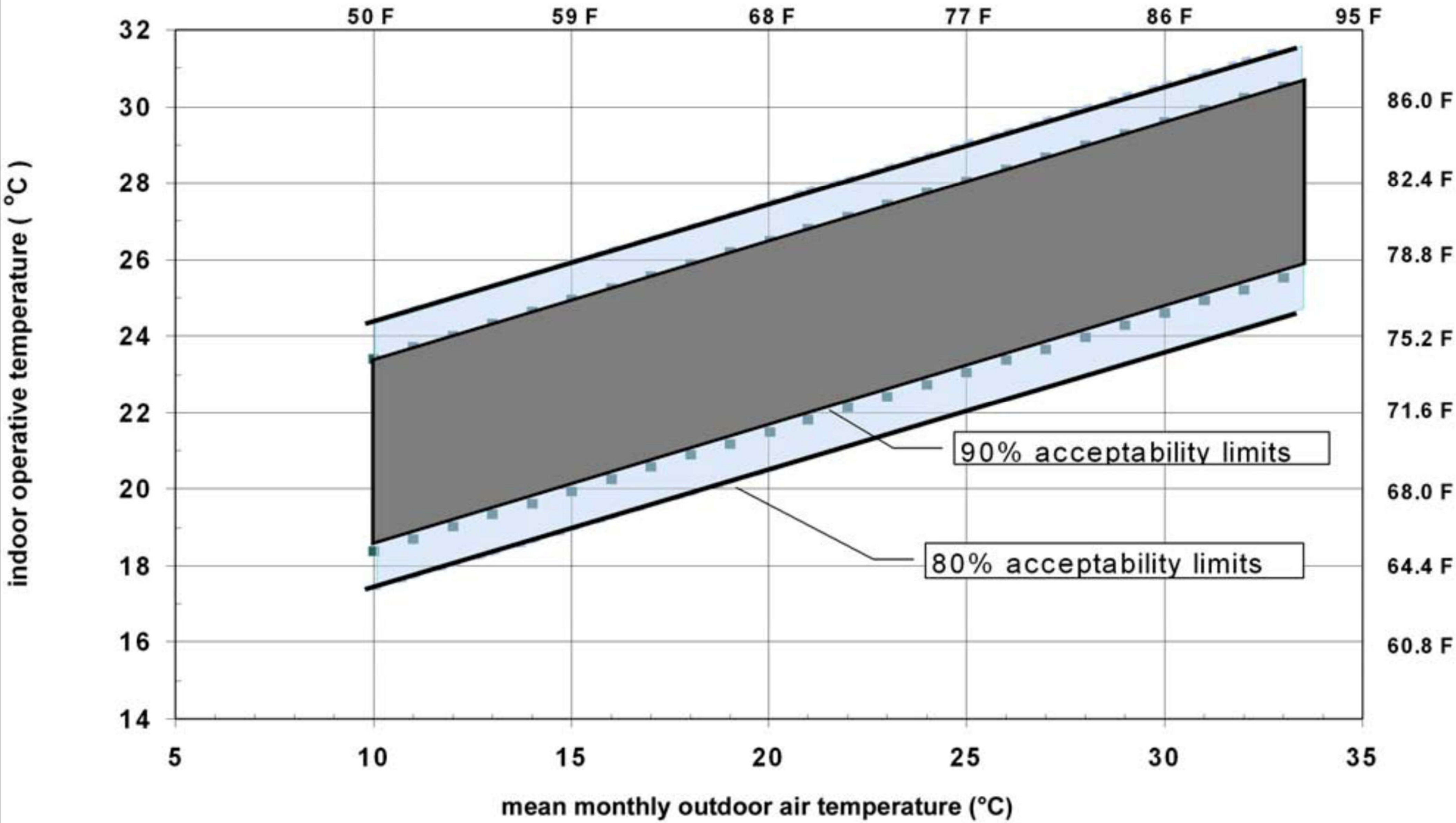
(Source: Butera, F. M., 1998. Principles of thermal comfort, *Renewable and Sustainable Energy Review*, 2 (1-2): 39-66.)

Basic concepts of adaptive thermal comfort



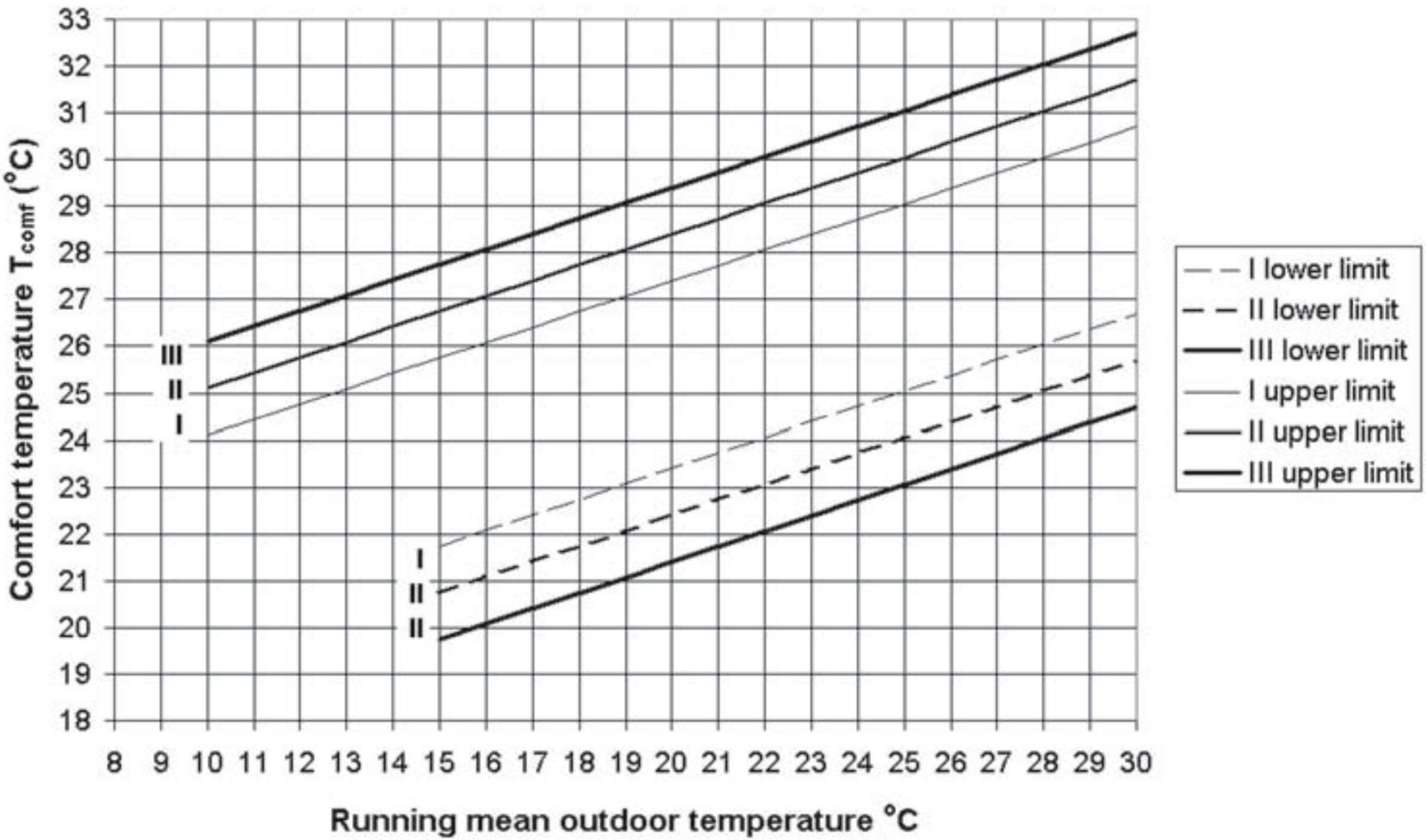


Acceptable operative temperature ranges for naturally conditioned spaces



(Source: ASHRAE Standard 55-2010)

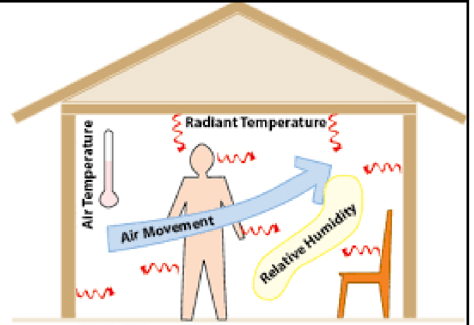
Acceptable operative temperature ranges for free-running naturally conditioned spaces (after standard EN15251)



(See also: Module 113: Determining thermal comfort in naturally conditioned buildings https://www.cibsejournal.com/cpd/modules/2017-07-nat/)

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

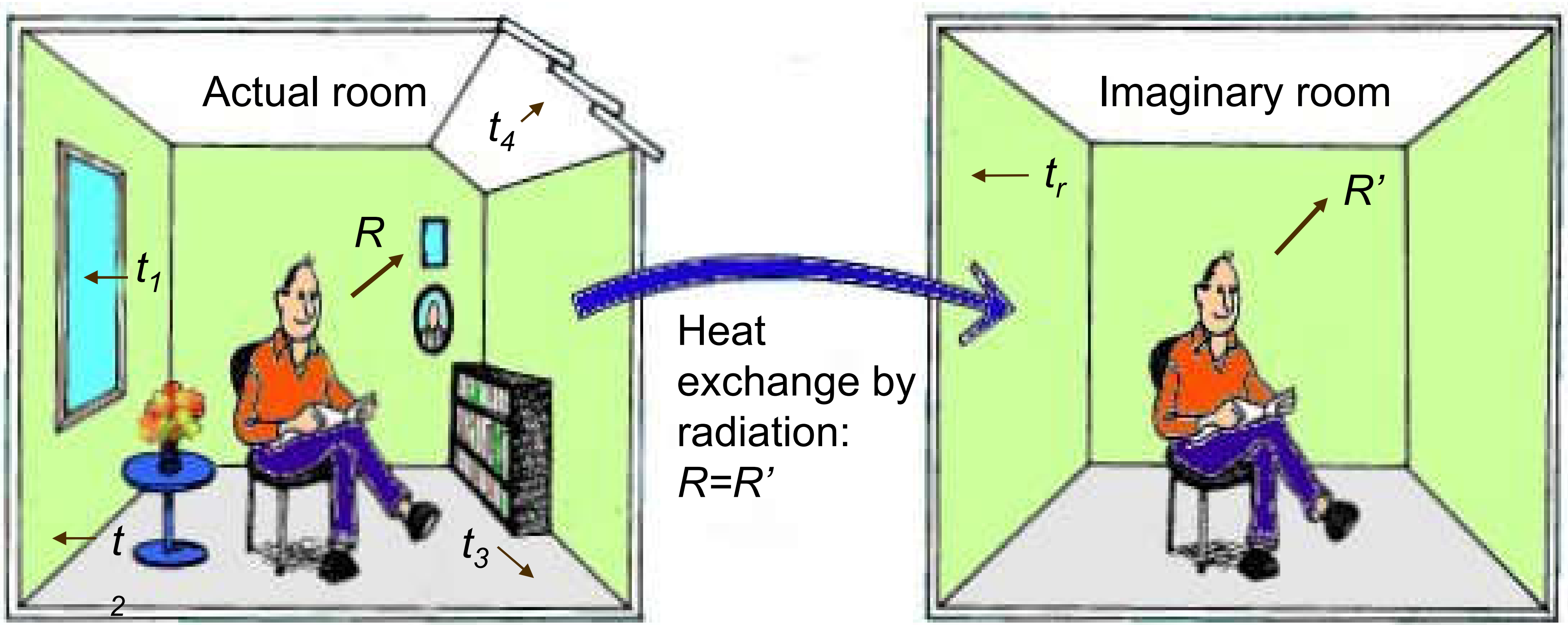
Influencing Factors



- What should be measured?
- Parameters to measure are:

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

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.

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

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

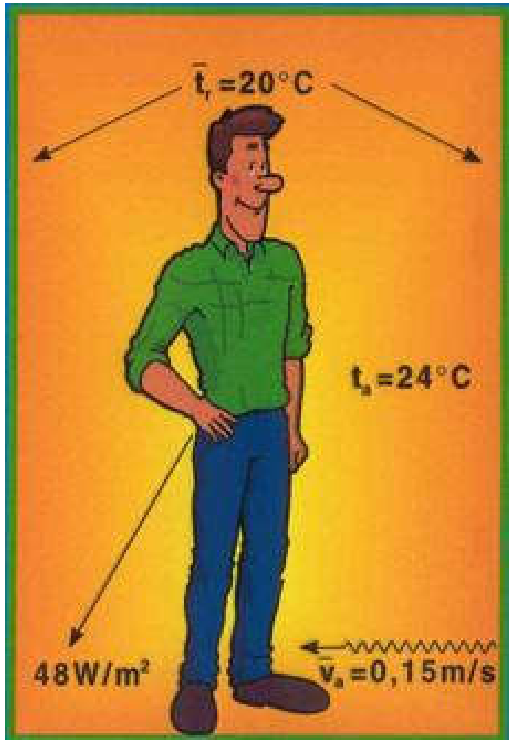
Environmental Indices

- **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)”

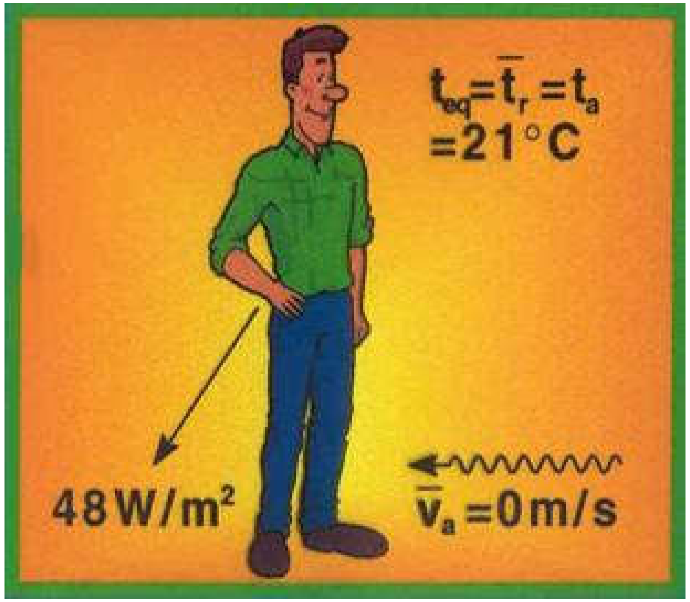
Environmental Indices

- **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)

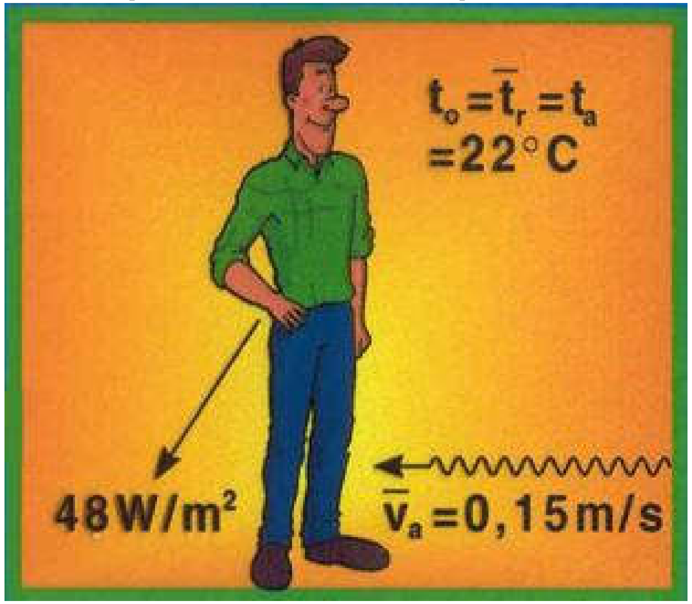
Operative and Equivalent Temperature



Operative temperature



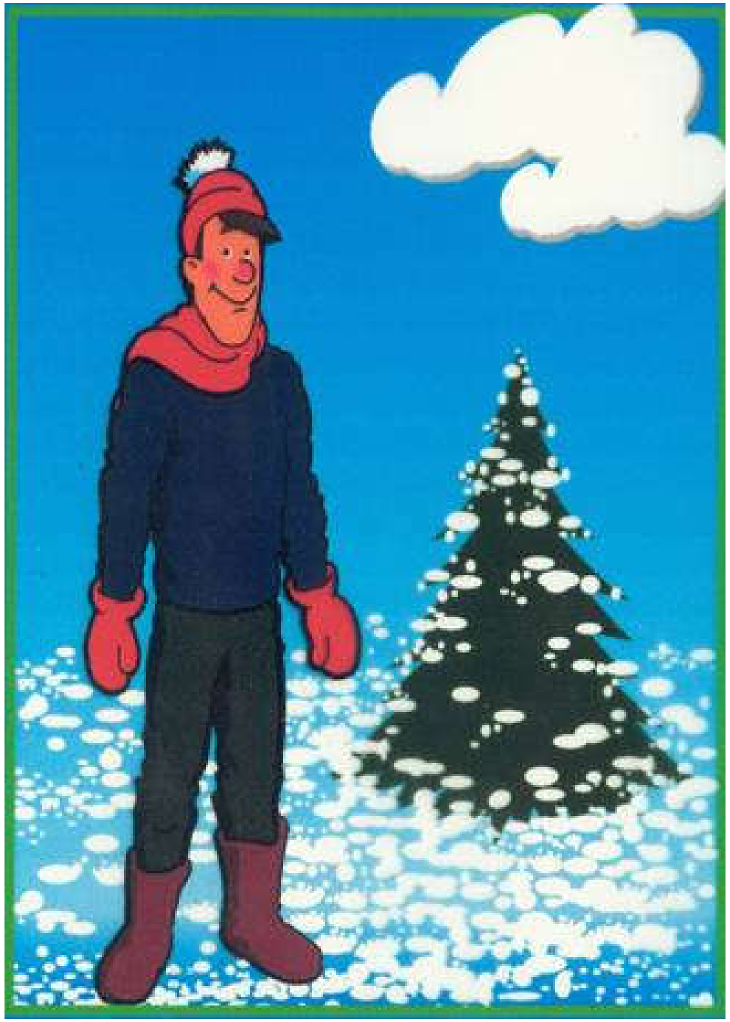
Equivalent temperature



Combines DBT & MRT

Combines DBT, MRT & air velocity

Operative and Equivalent Temperature



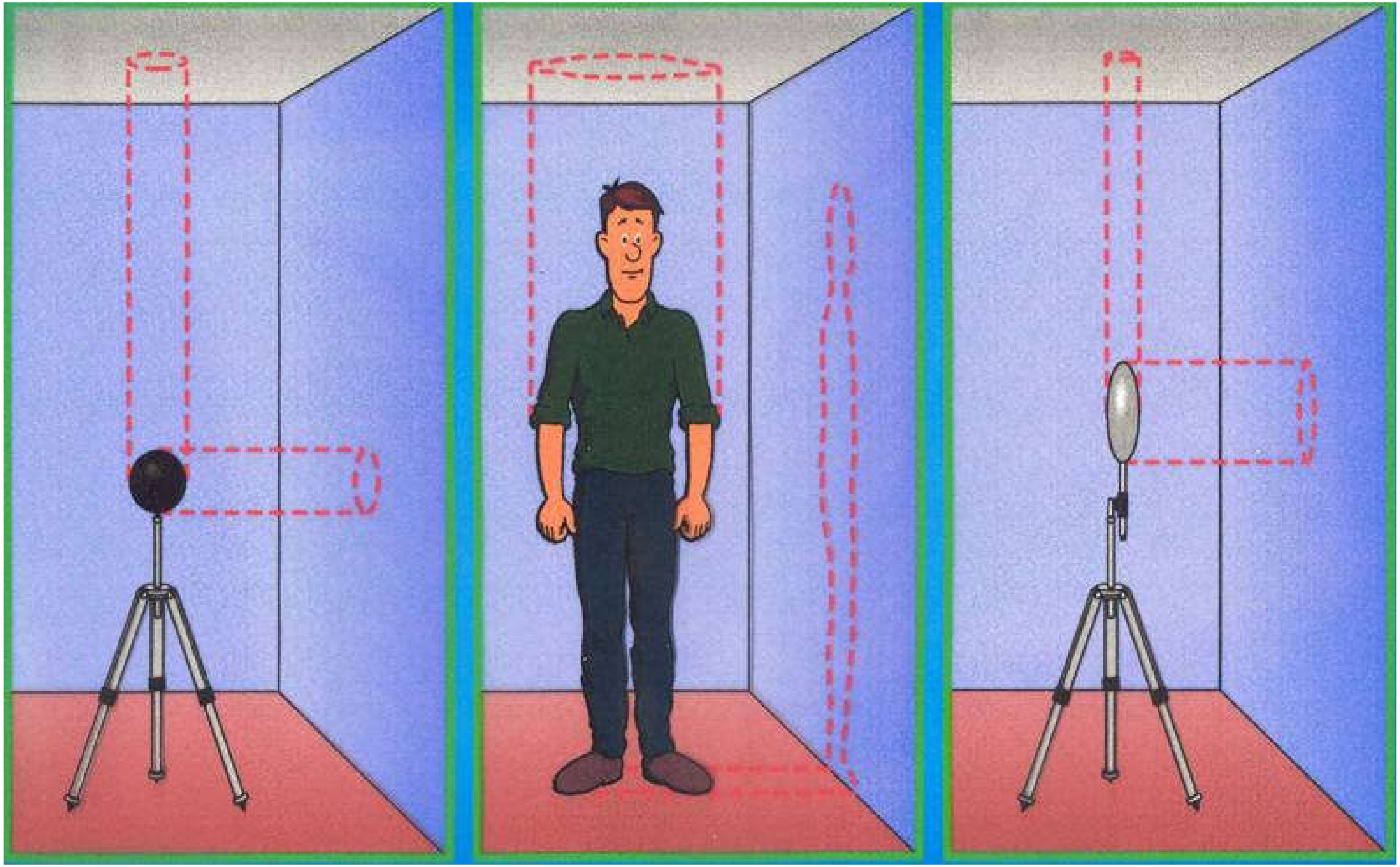
Operative temperature

Combines DBT & MRT

Equivalent temperature

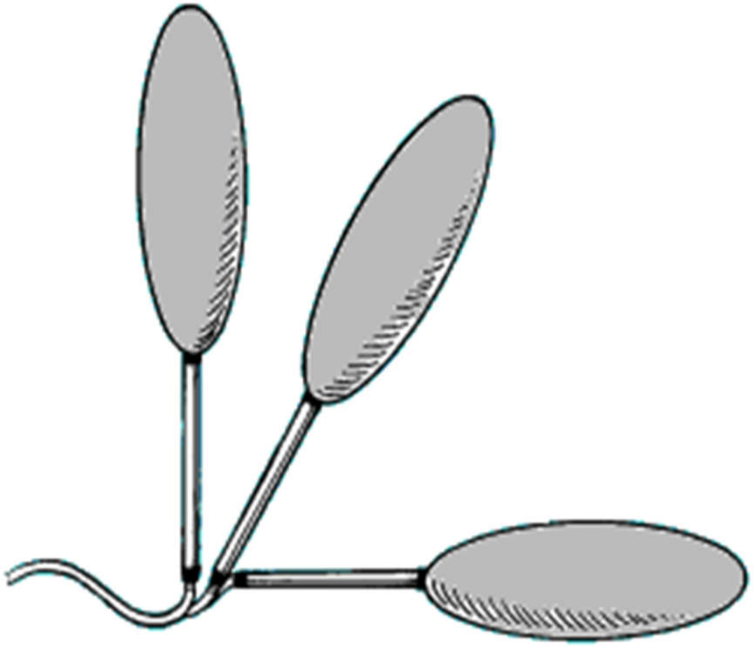
Combines DBT, MRT & air velocity

Projected Area Factor



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

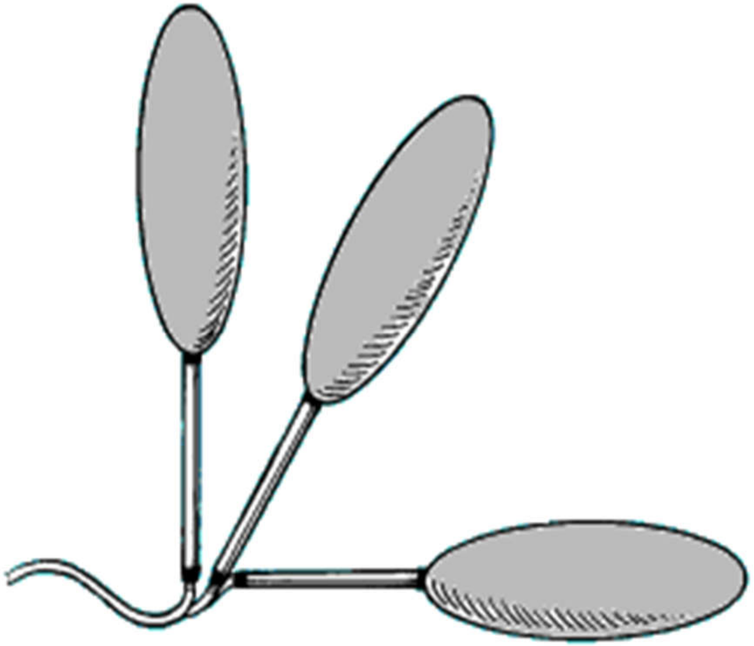
Operative Temperature



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

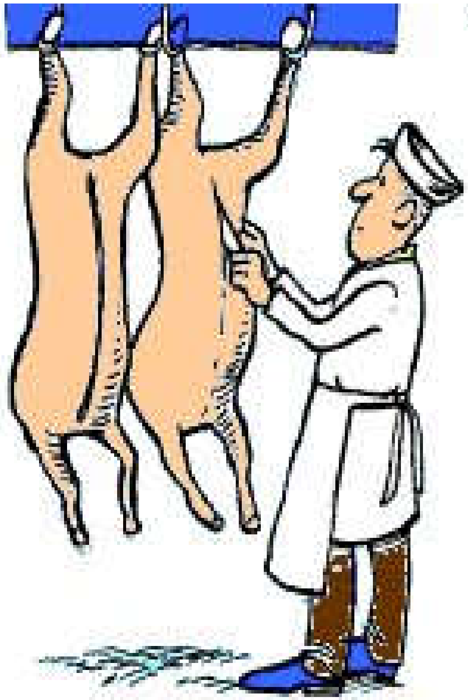
- Measure Operative Temperature: the transducer must have same heat exchange properties as an unheated mannequin (artificial human) dummy.

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)

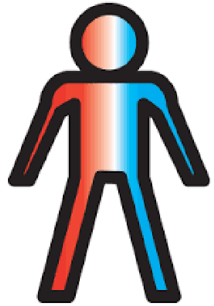


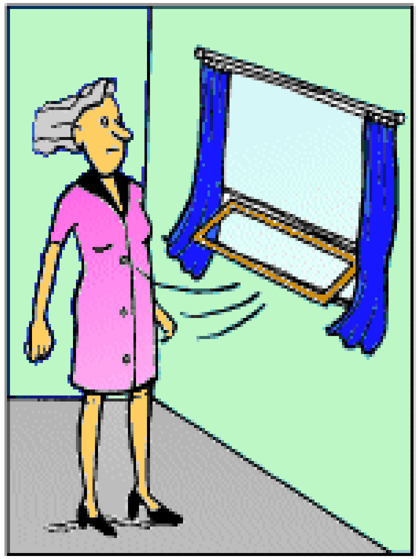
1.7 clo
2.5 Met
RH=50%
t_{co}=6°C

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

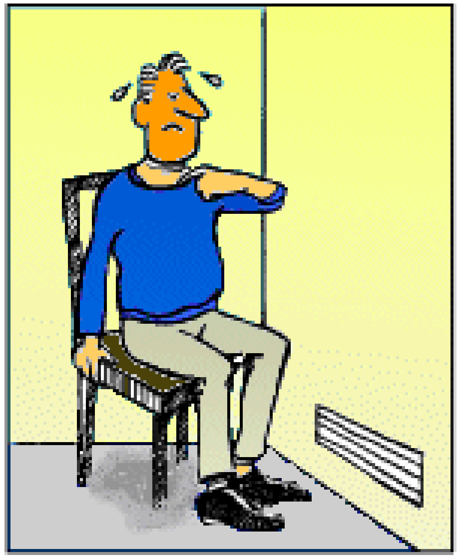
Local Thermal Discomfort



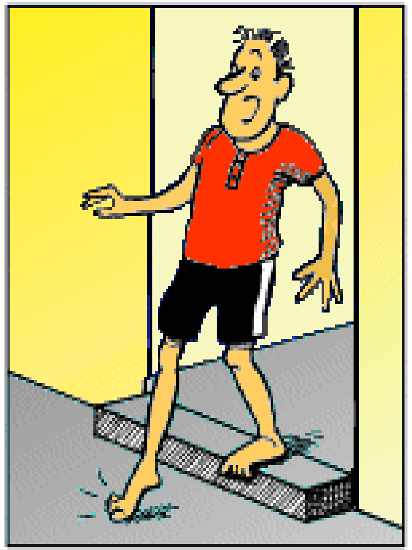


- Draught

- Radiation Asymmetry

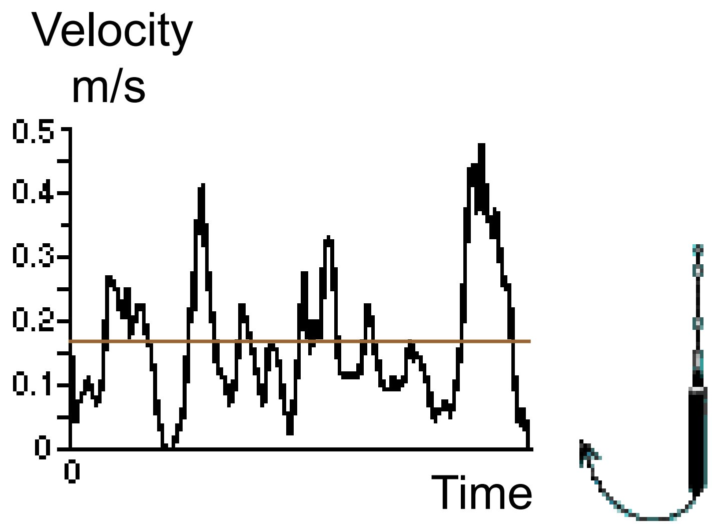


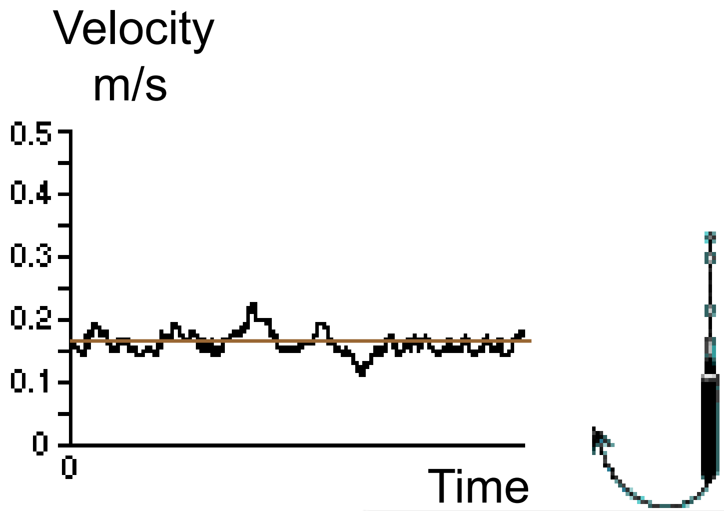
- Vertical Air Temperature Differences.

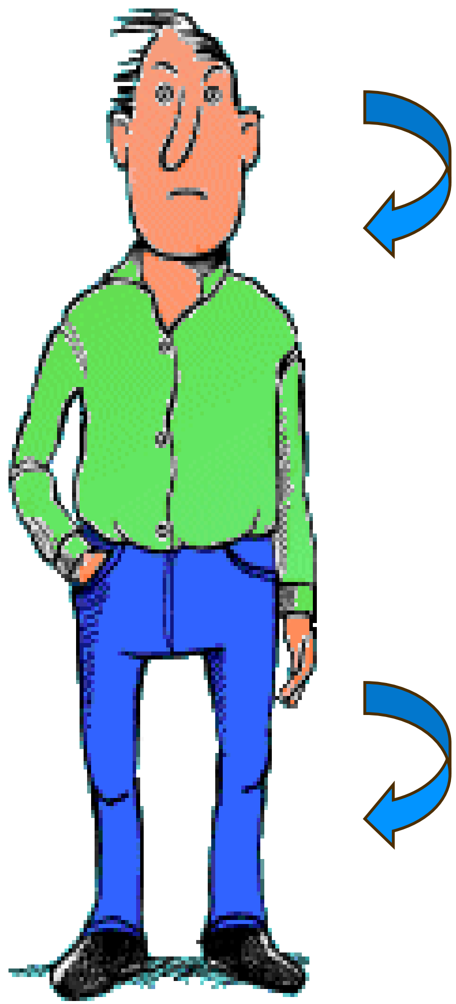


- Floor temperature

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

$$Draft\ Rating\ (\%) = (34 - Tx)\ (V_x - 0.05)^{0.62}(0.37 \times V_x \times T_u + 3.14)$$

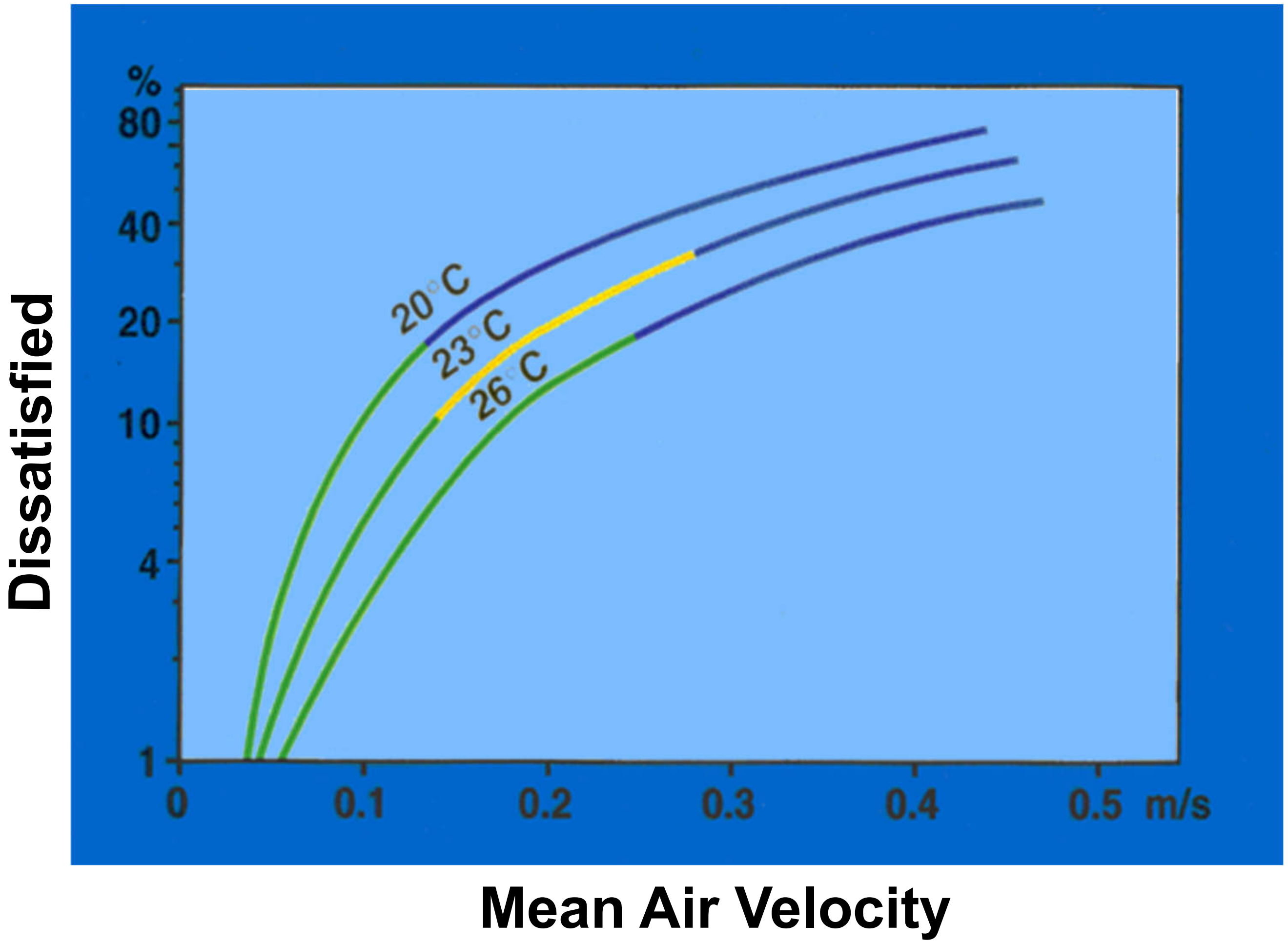
where,

t = local air temperature (°C)

V_x = local air speed (m/s)

T_u = turbulence intensity (%)

Draught



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

$$Effective\ Draft\ Temperature\ (°F) = (T_x - T_{avg}) - 0.07(V_x - 30)$$

where,

T_x = local air temperature (°F)

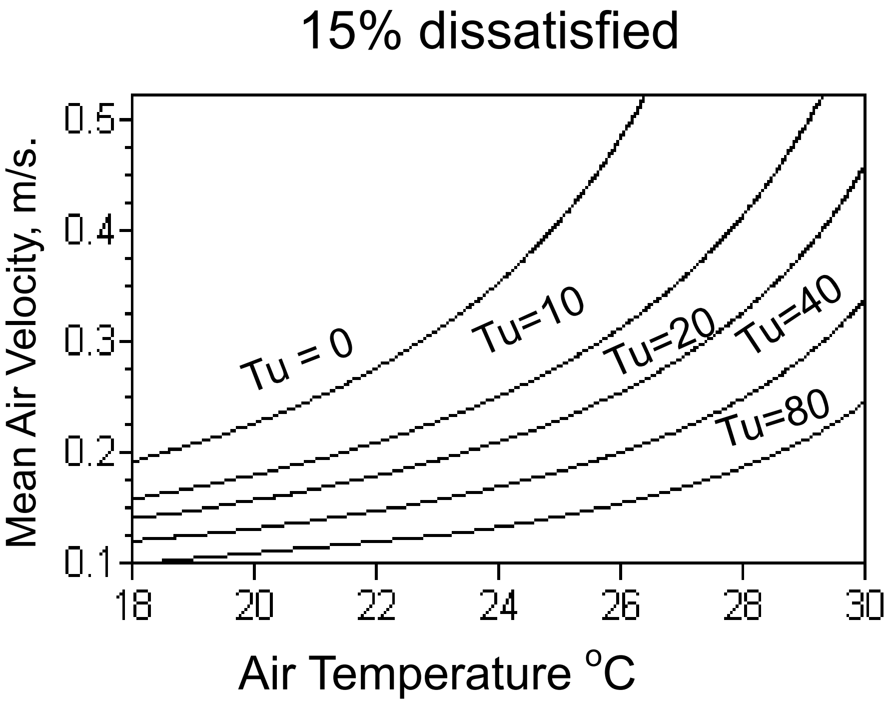
T_{avg} = room average air temperature (°F)

V_x = local air velocity (ft/min) or (fpm)

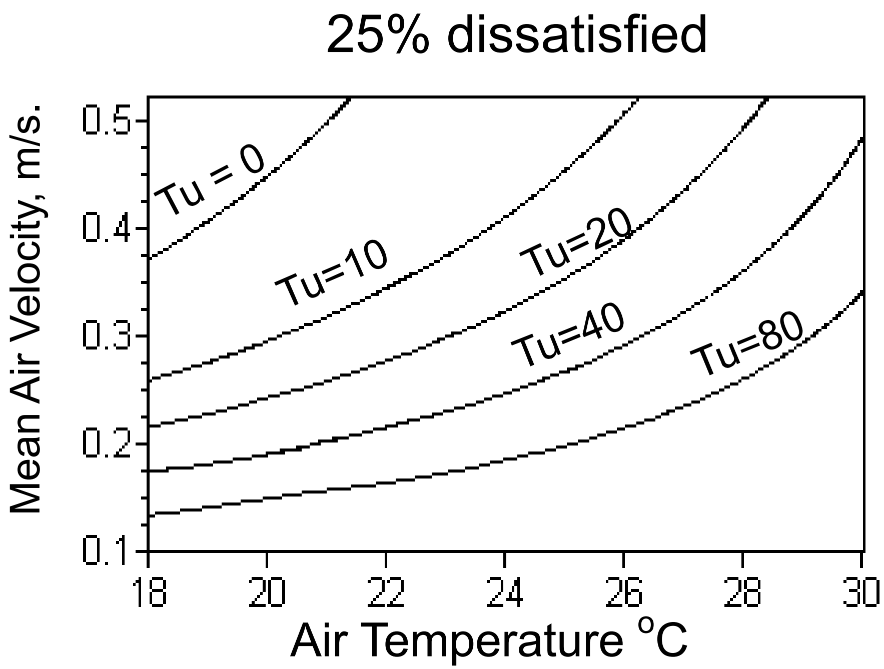
Effective Draft Temperature (EDT) [SI units]

EDT =[1.8(Tx - Tavg) -0.07(196.85*Vx - 30)]

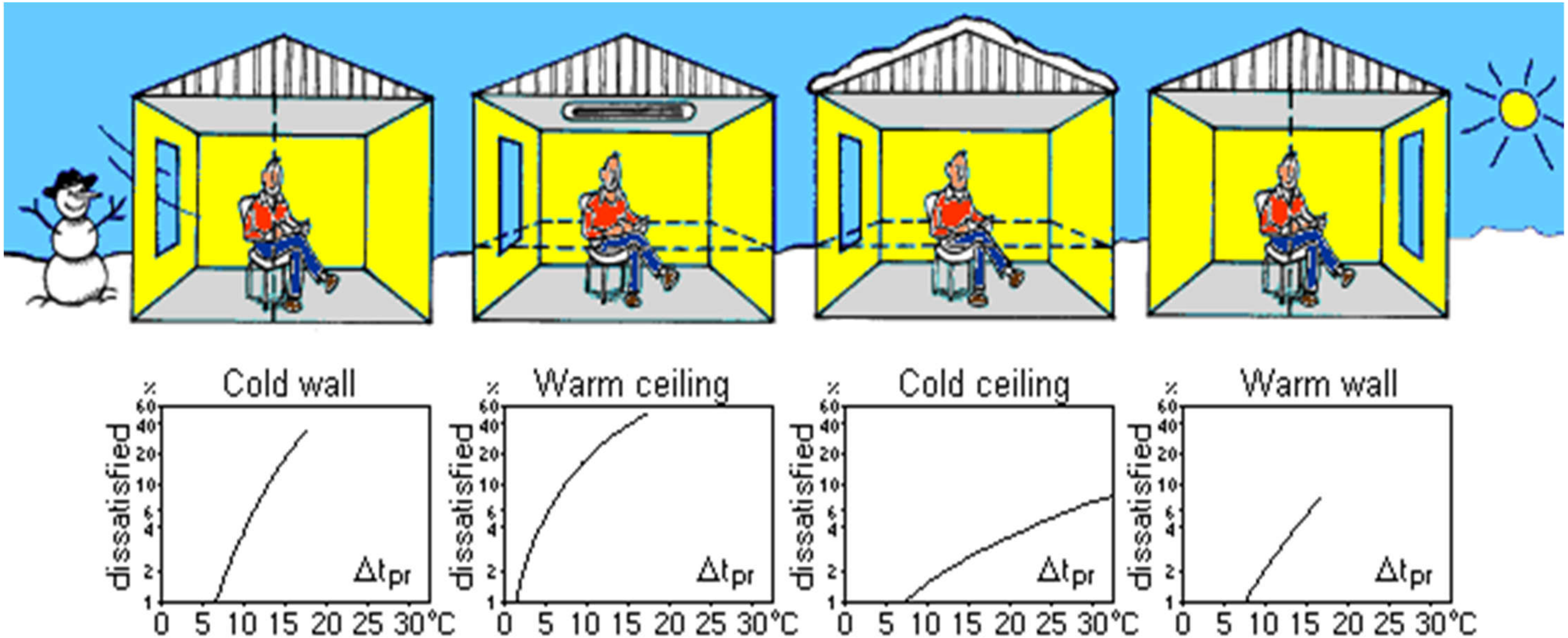
Evaluating Draught Rate



- 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

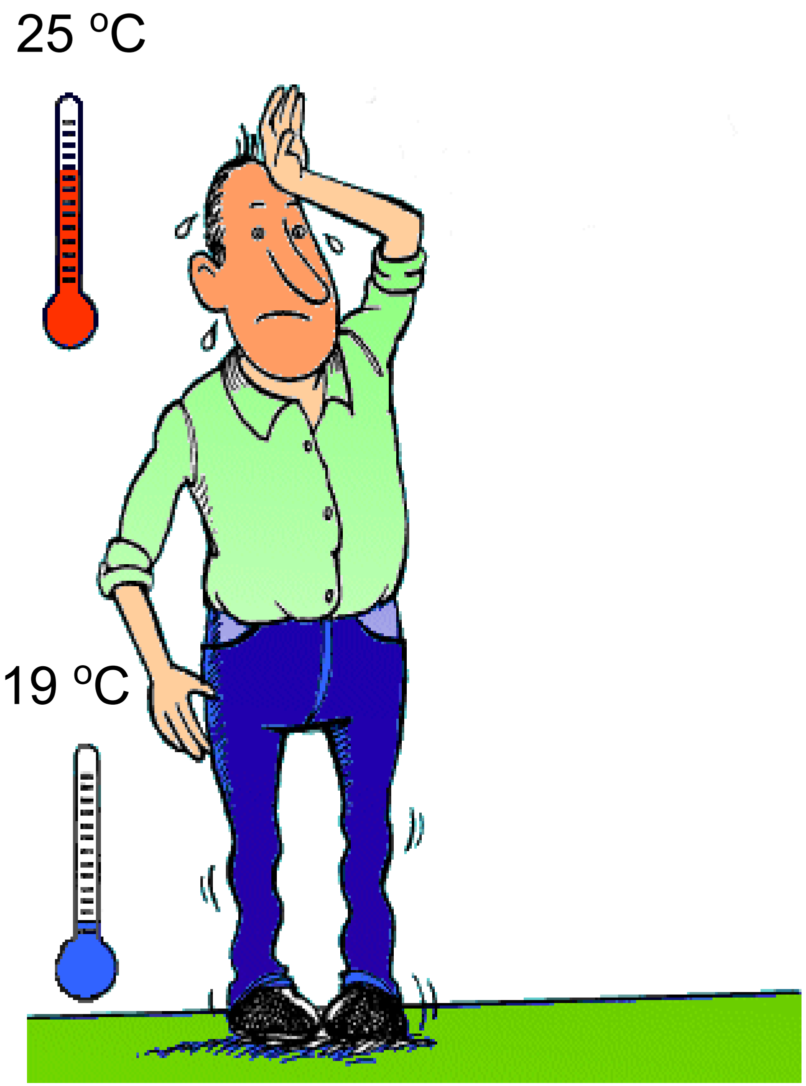


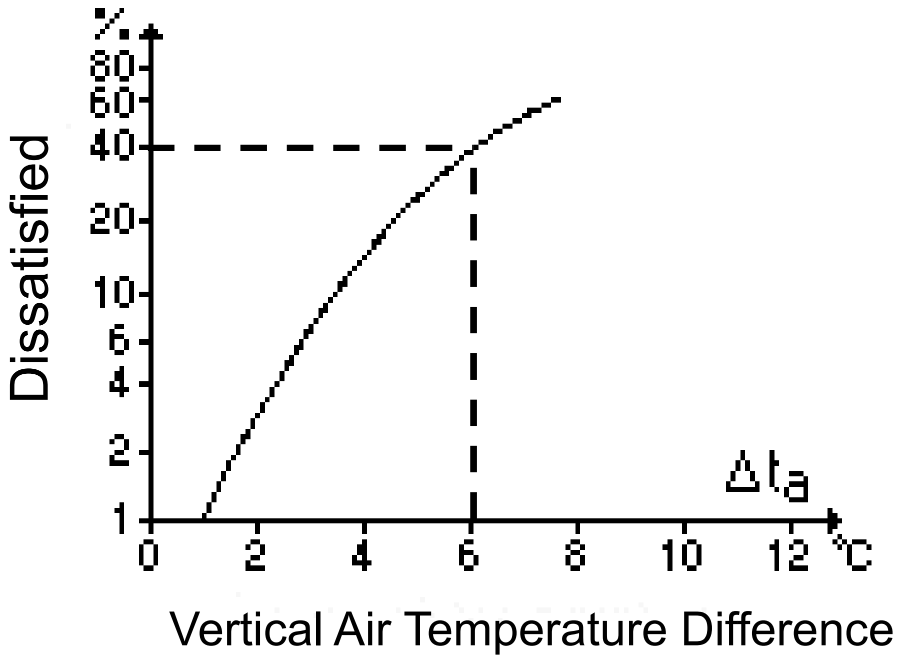
Radiation Asymmetry



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

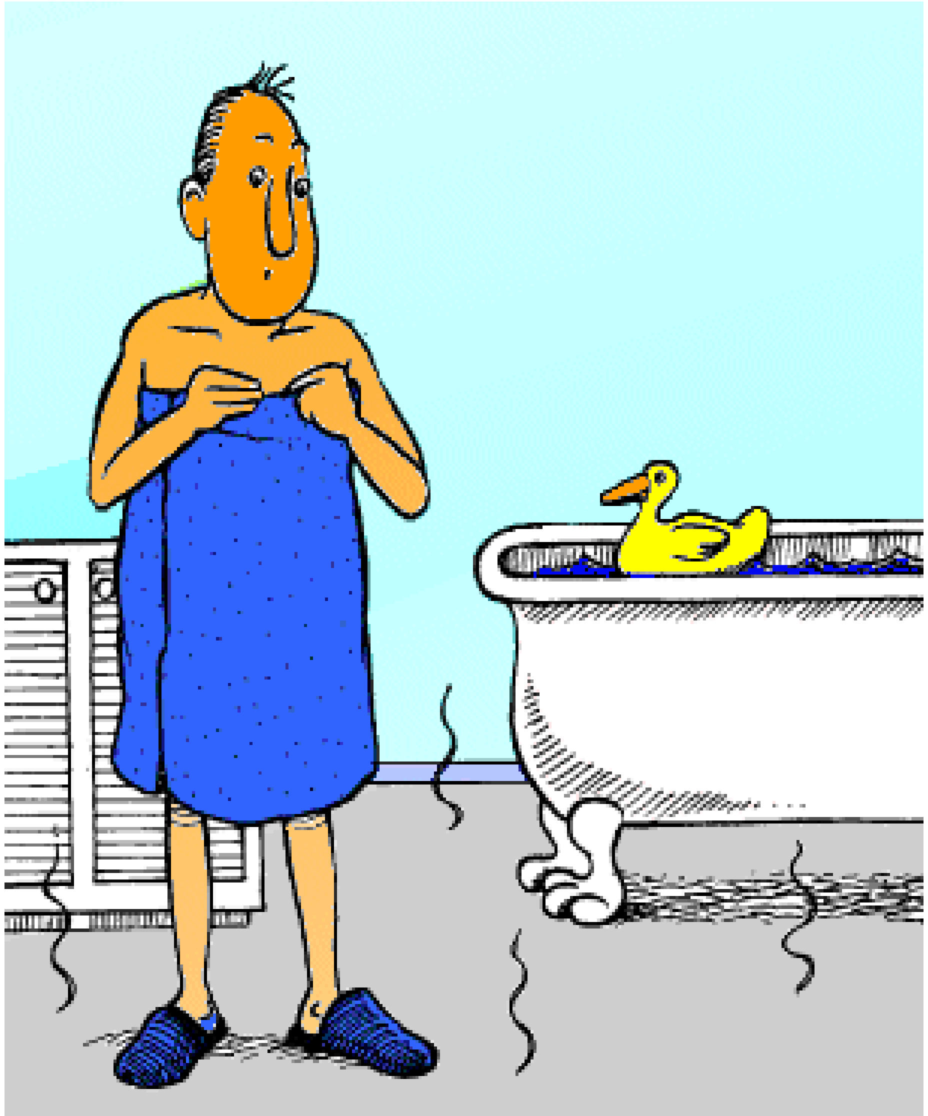
Vertical Air Temperature Difference

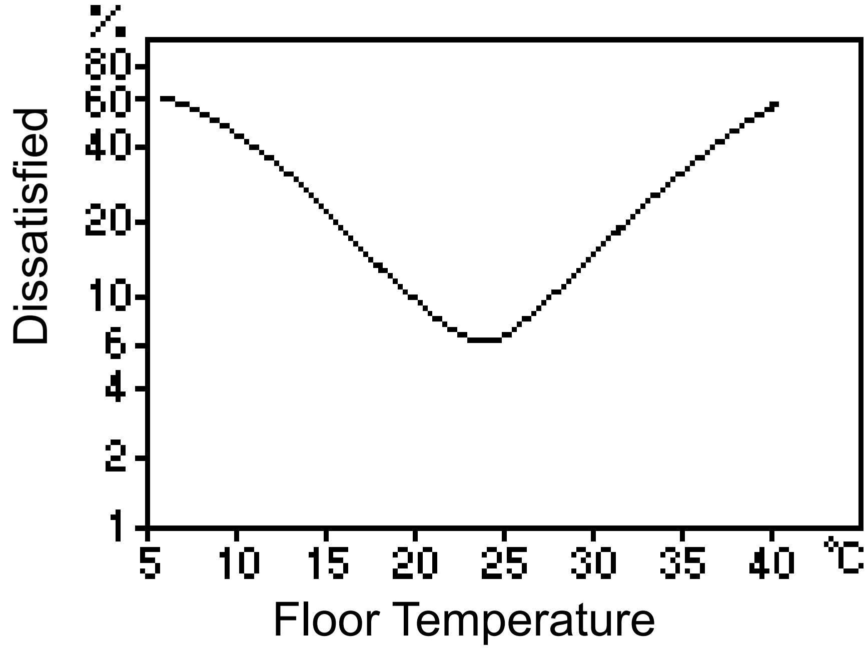




- Vertical Air Temperature Difference is the difference between Air Temperature at ankle and neck level

Floor Temperature





- Acceptable floor temperatures ranging from 19 to 29 °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

Measurements and Analysis

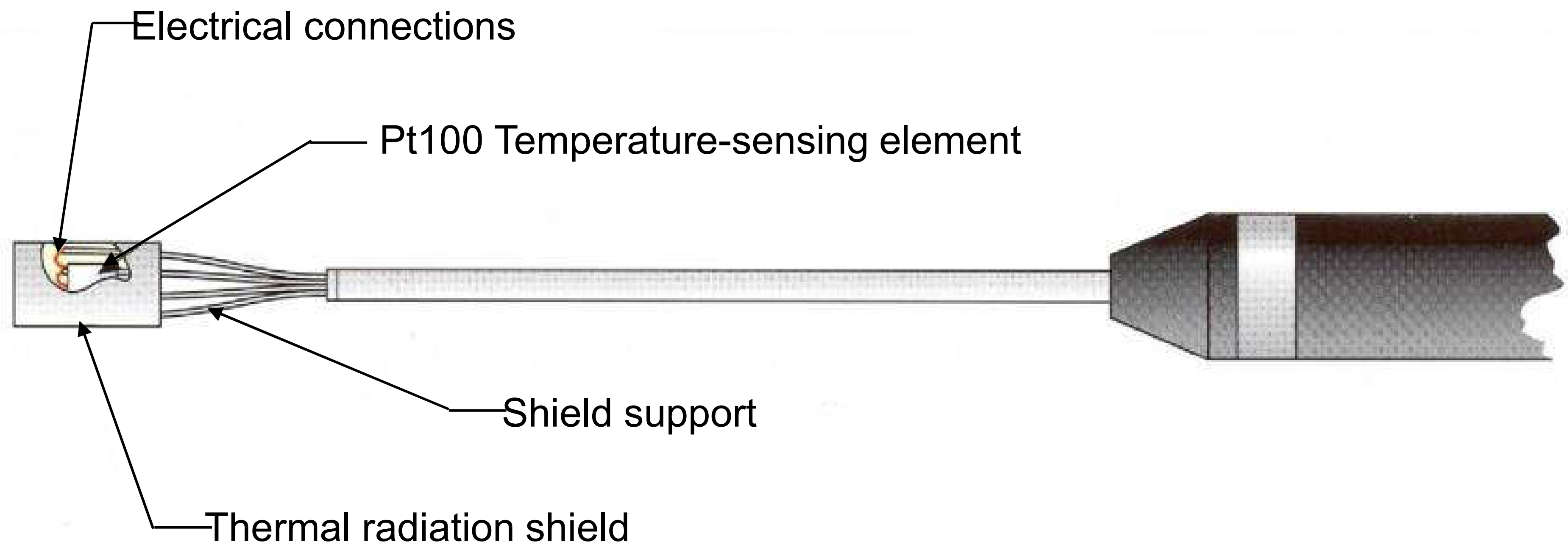
- Collection of thermal comfort data

Transducers

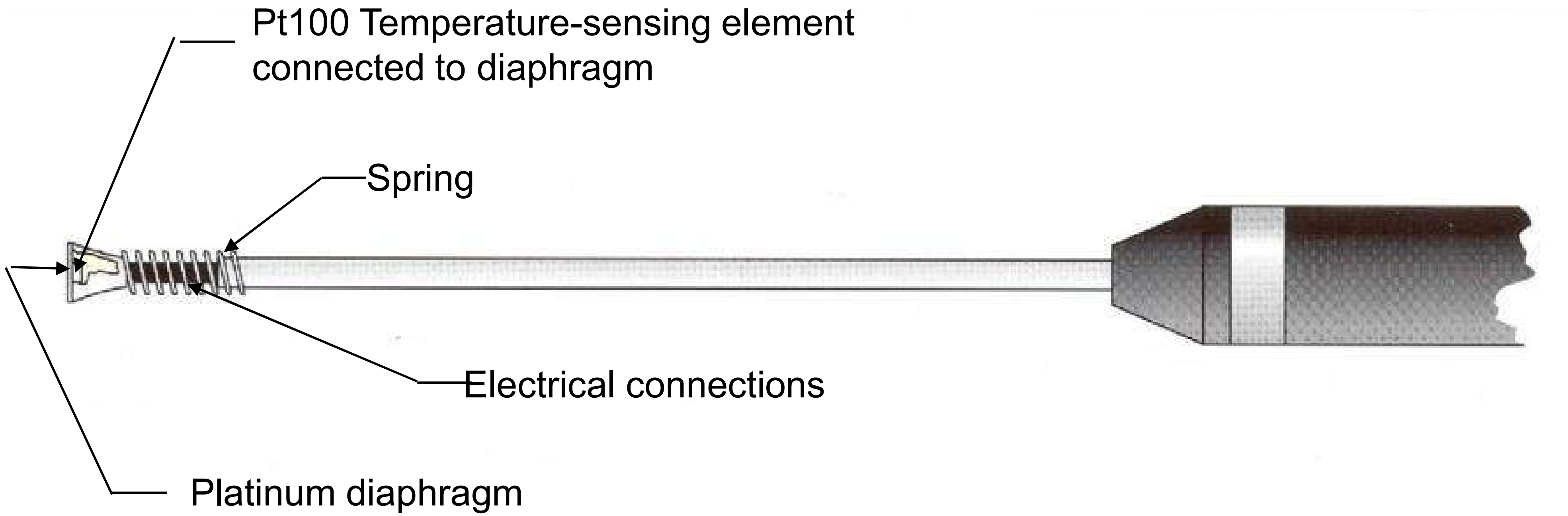
- Operative Temperature
- Air Velocity
- Radiant Temperature Asymmetry
- Air Temperature
- Humidity
- Surface Temperature
- WBGT
- Dry Heat Loss

(Examples of measurement instruments for thermal comfort: https://www.deltaohm.com/en/measure/thermal-comfort/)

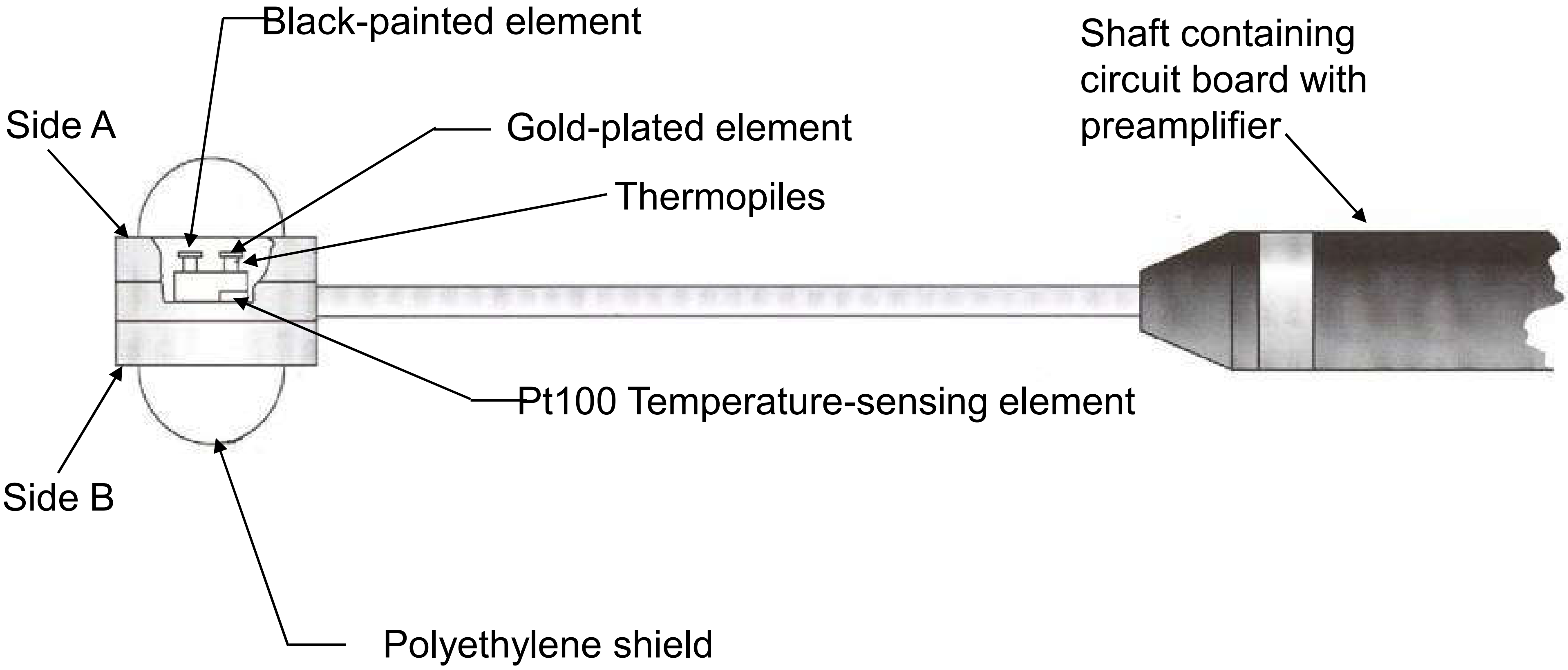
Air Temperature Transducer



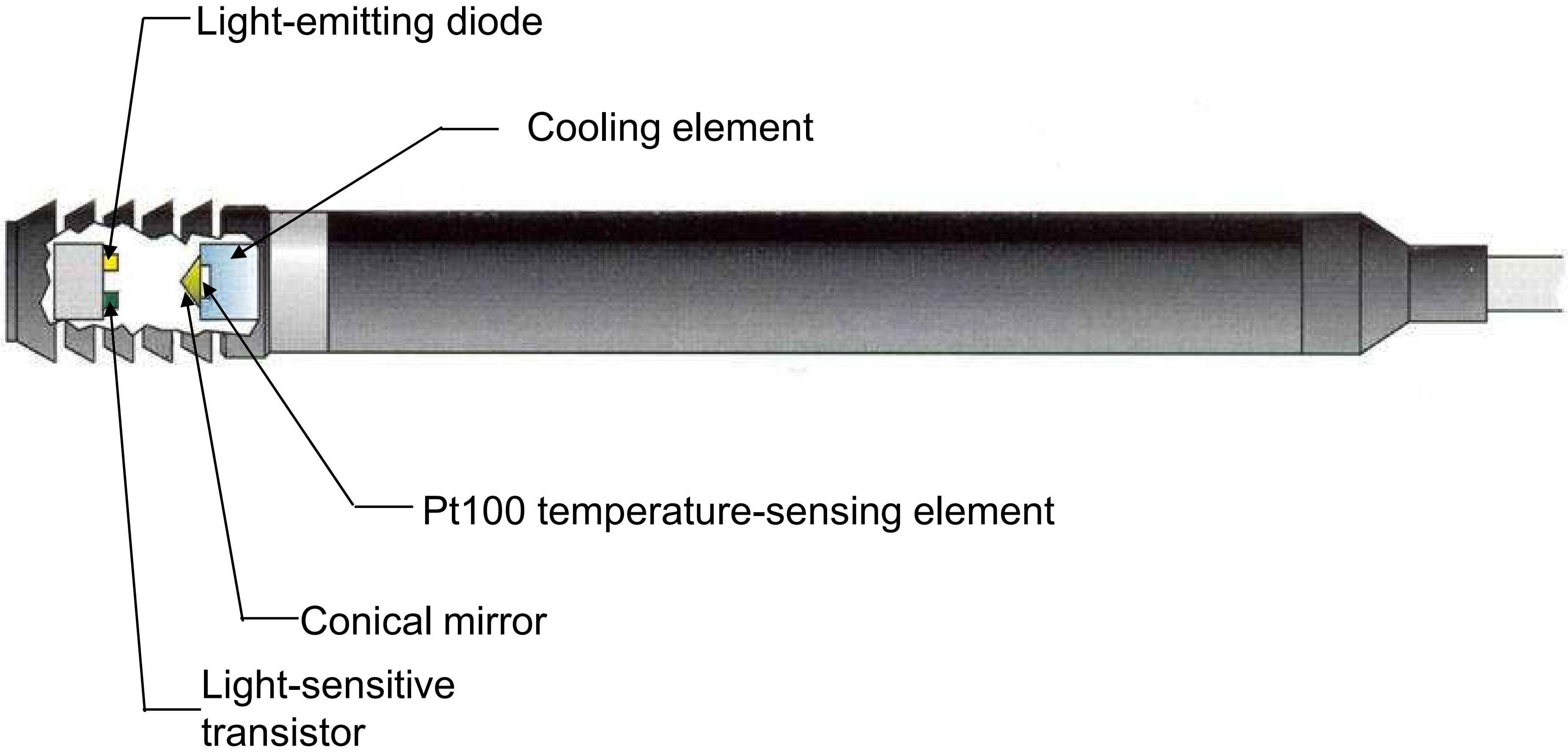
Surface Temperature Transducer



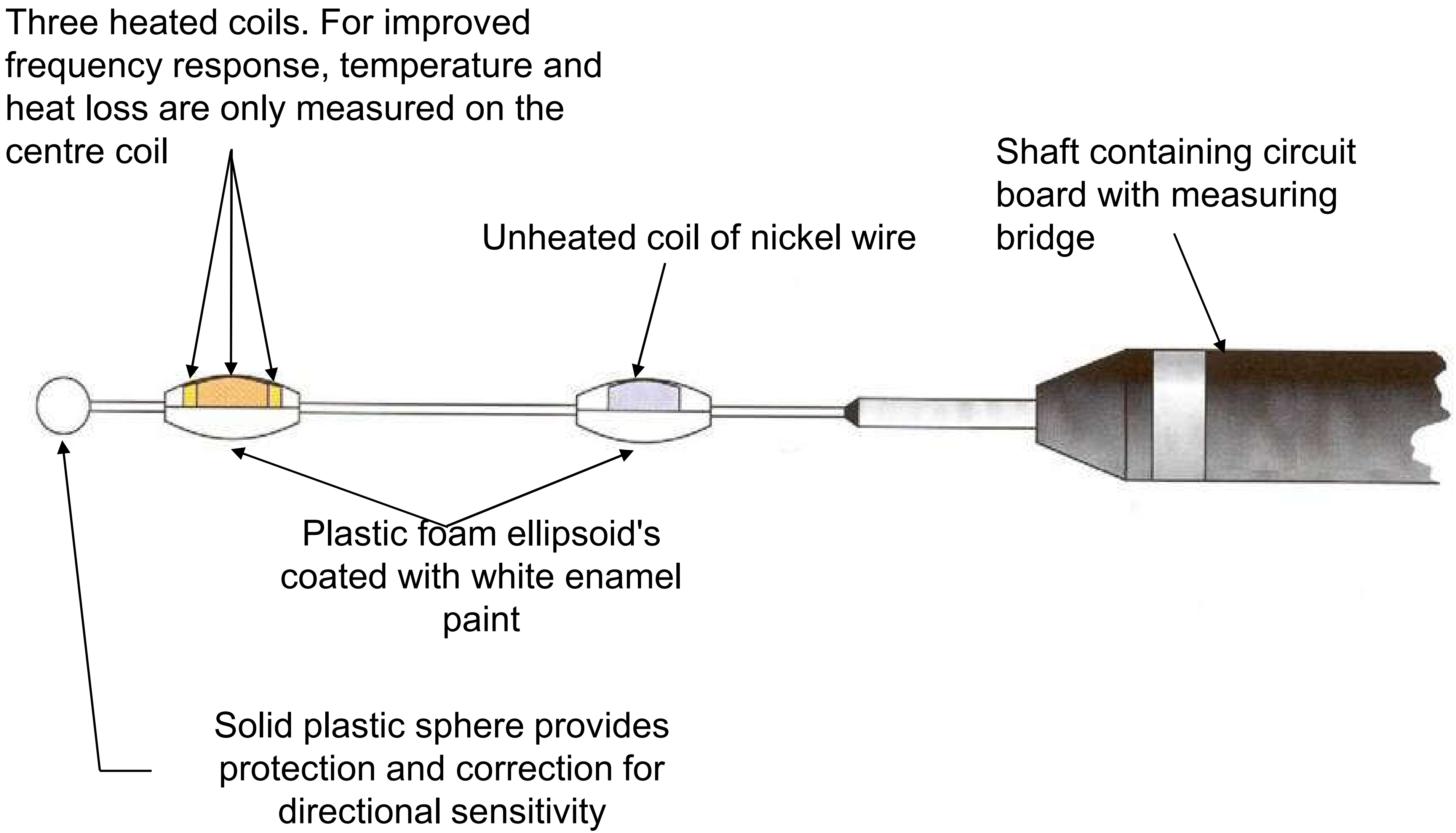
Radiant Temperature Asymmetry Transducer



Humidity Transducer



Air Velocity Transducer



An Example of Measurement

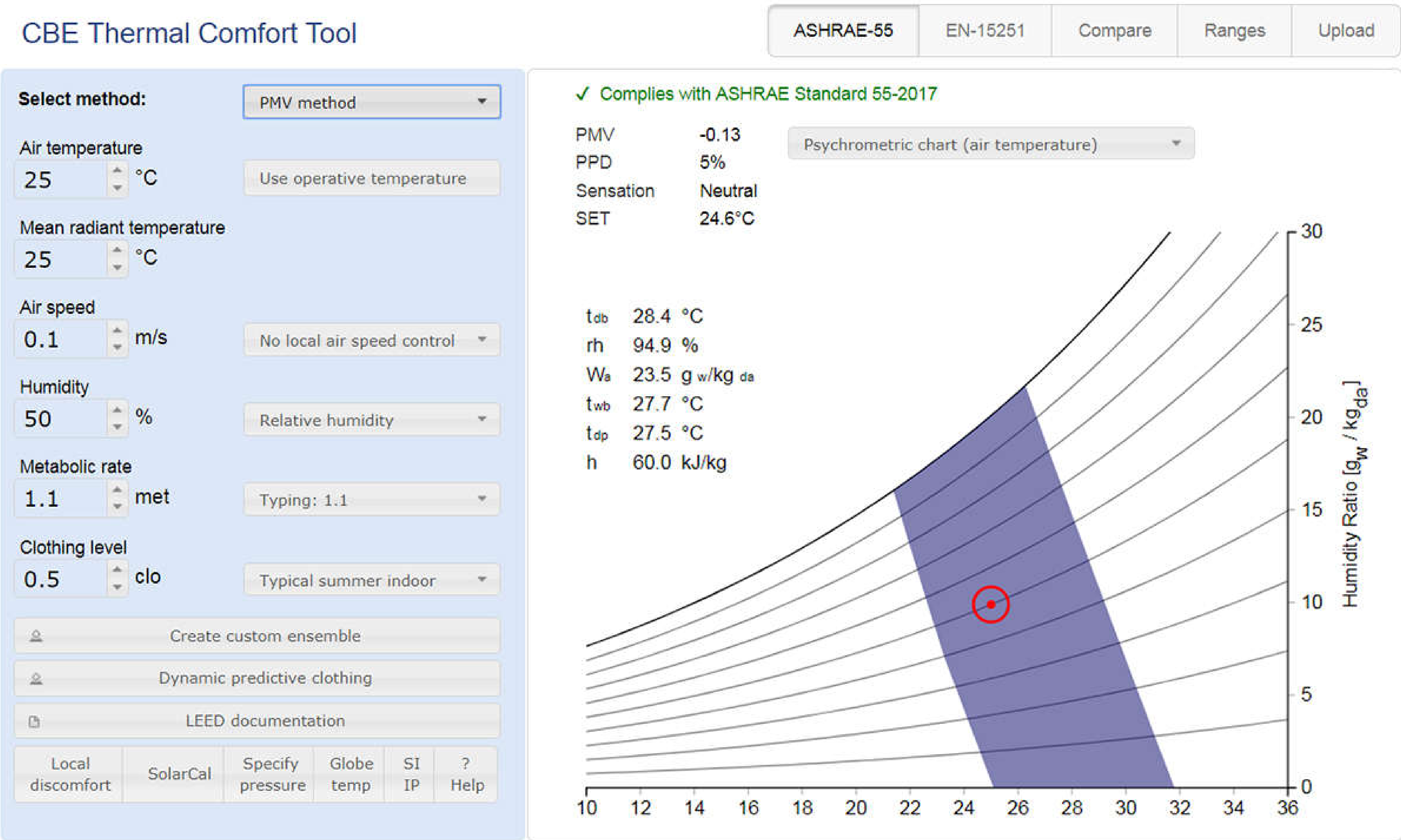
Comfort data logger with comfort transducer:

• 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.

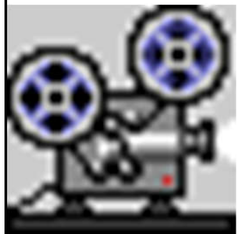
CBE Thermal Comfort Tool https://comfort.cbe.berkeley.edu/ - from Center for the Built Environment (CBE), UC Berkeley



(Source: https://cbe.berkeley.edu/research/thermal-comfort-tool/)

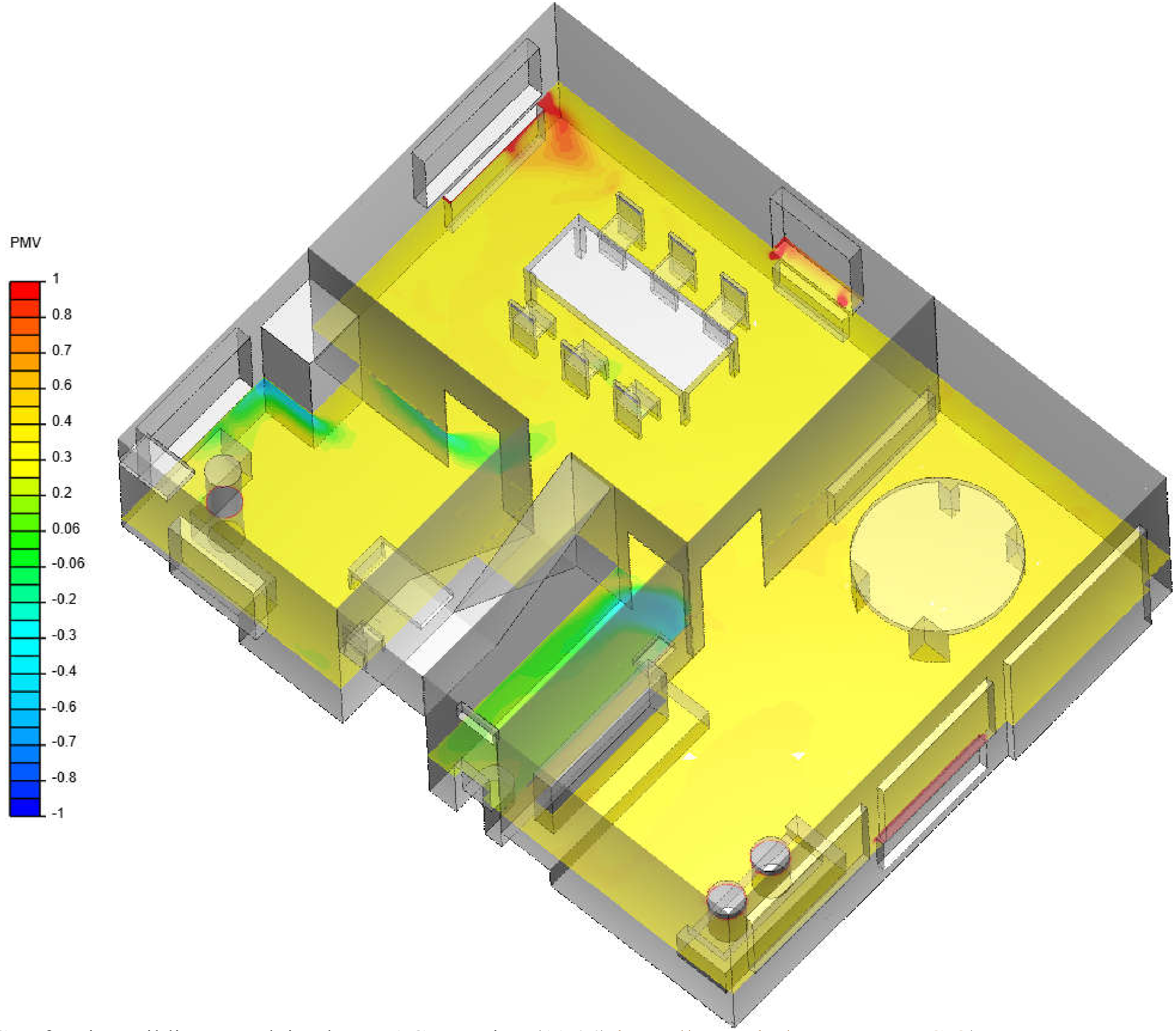
Measurements and Analysis

- CBE Thermal Comfort Tool (UC Berkeley): training videos https://comfort.cbe.berkeley.edu/
  - Overview - CBE thermal comfort tool (1:20) https://youtu.be/ebEGeKAKa84
  - Adaptive method ASHRAE 55 - CBE thermal comfort tool (2:23) https://youtu.be/56GDp2LHBjQ
  - PMV ASHRAE 55 - CBE thermal comfort tool (5:19) https://youtu.be/5WkH2SN664k
  - Local thermal discomfort - CBE thermal comfort tool (3:08) https://youtu.be/ykcJBW5Zdks



(See also: http://centerforthebuiltenvironment.github.io/comfort_tool/)

Thermal comfort analysis using computational fluid dynamics (CFD)



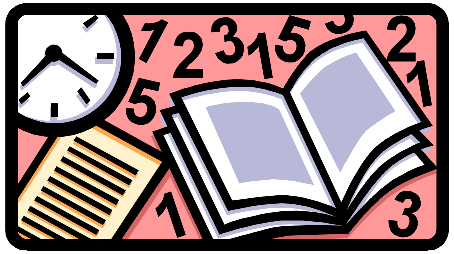
(Video: Thermal Comfort in Buildings Explained - HVACR Design (11:04) https://youtu.be/yEWT_XmqCtQ)

(Source: https://www.simscale.com/blog/2019/08/radiation-heat-transfer-release/)

Further Reading

- Videos:
  - 02 Thermal Comfort (6:41) https://youtu.be/BTdiimklSqo
  - Standard and adaptive approach for thermal comfort (Federico Butera) (11:55) https://youtu.be/SwZ1FEgangE
  - Indoor Climate and Thermal Comfort Assessment for ASHRAE 55 with CFD (33:22) https://youtu.be/wT3IMpPsJ6k
- What Is ASHRAE 55? Basics of Thermal Comfort https://www.simscale.com/blog/2019/08/what-is-ashrae-55-thermal-comfort/

References



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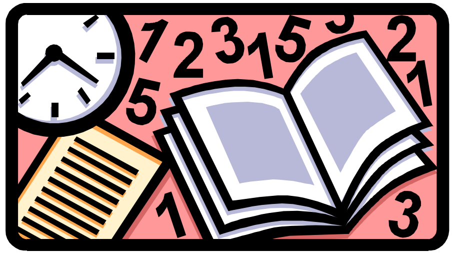

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