MEBS6006 Environmental Services I

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Thermal Comfort

Dr. Sam C M Hui

Department of Mechanical Engineering

The University of Hong Kong

E-mail: cmhui@hku.hk

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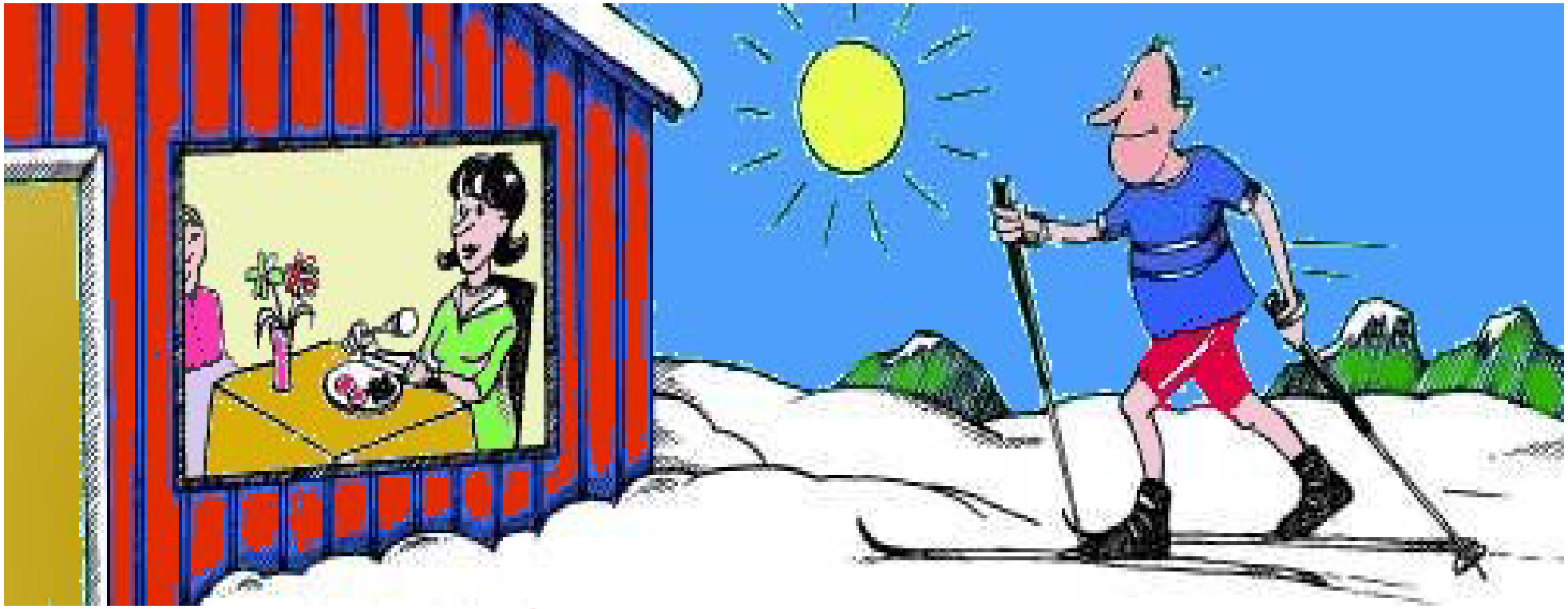
Acknowledgement

- Cartoons and some figures are taken from:
  - http://www.innova.dk/

* The need to define “comfortable environment” arose from the AC industry

What is Thermal Comfort?



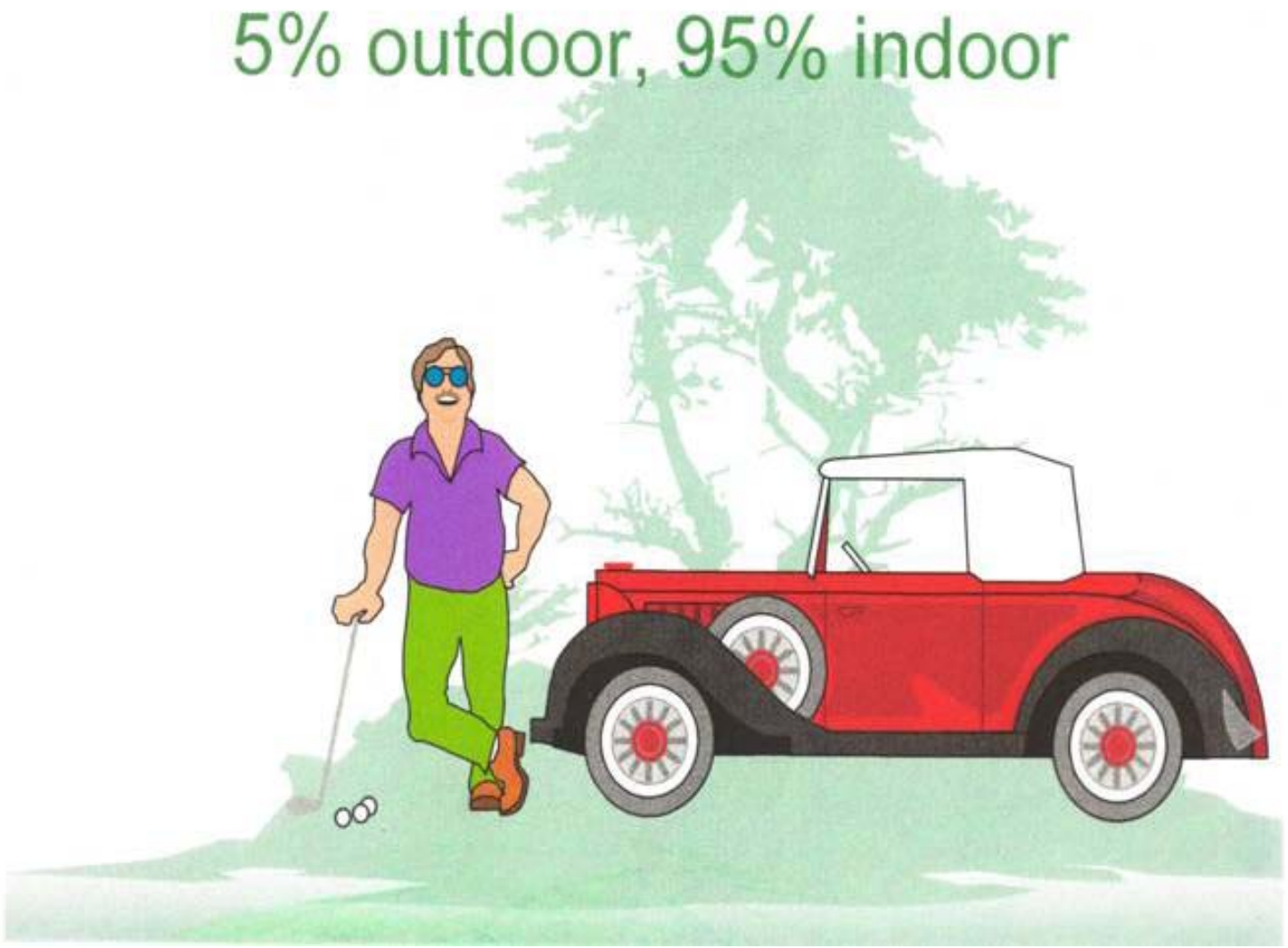
Definition

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

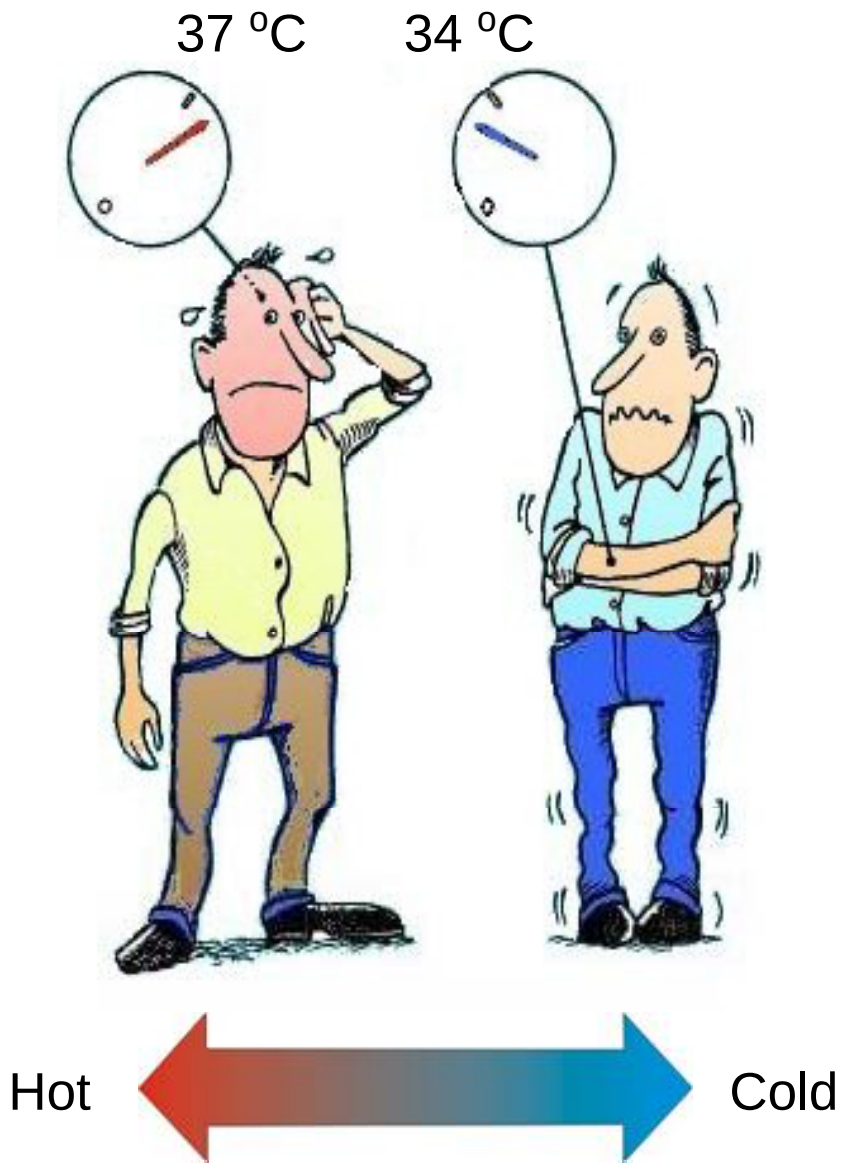
ISO 7730

Thermal Environments

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

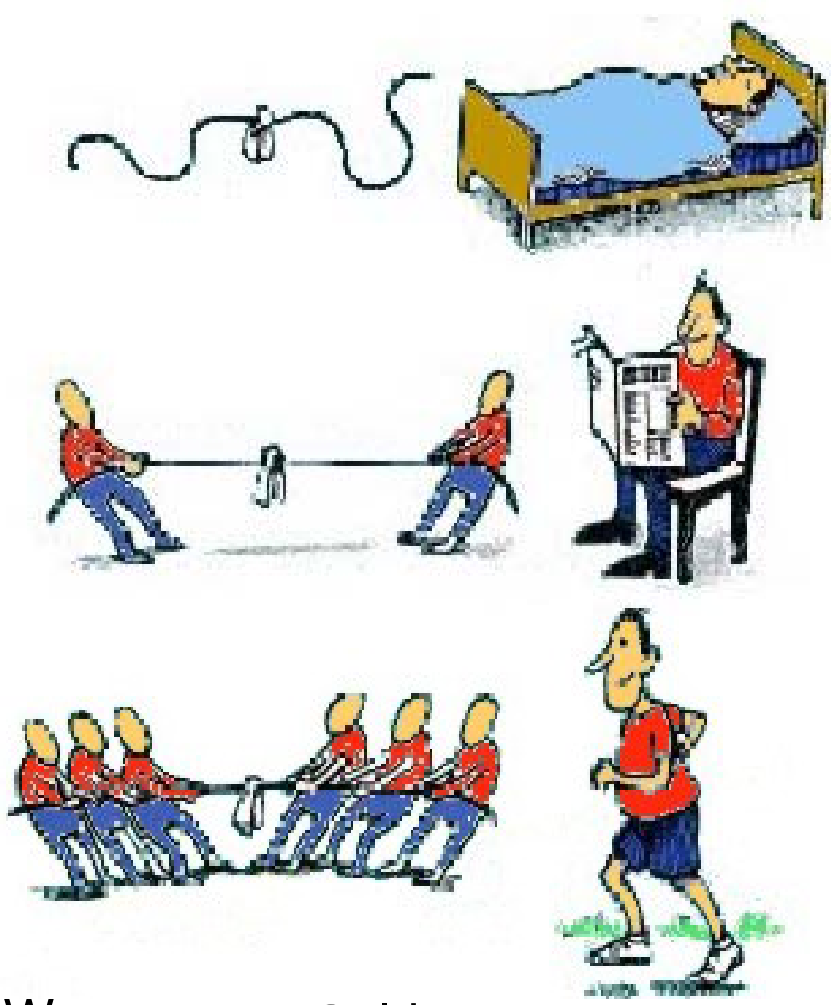


Body Temperature



- 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



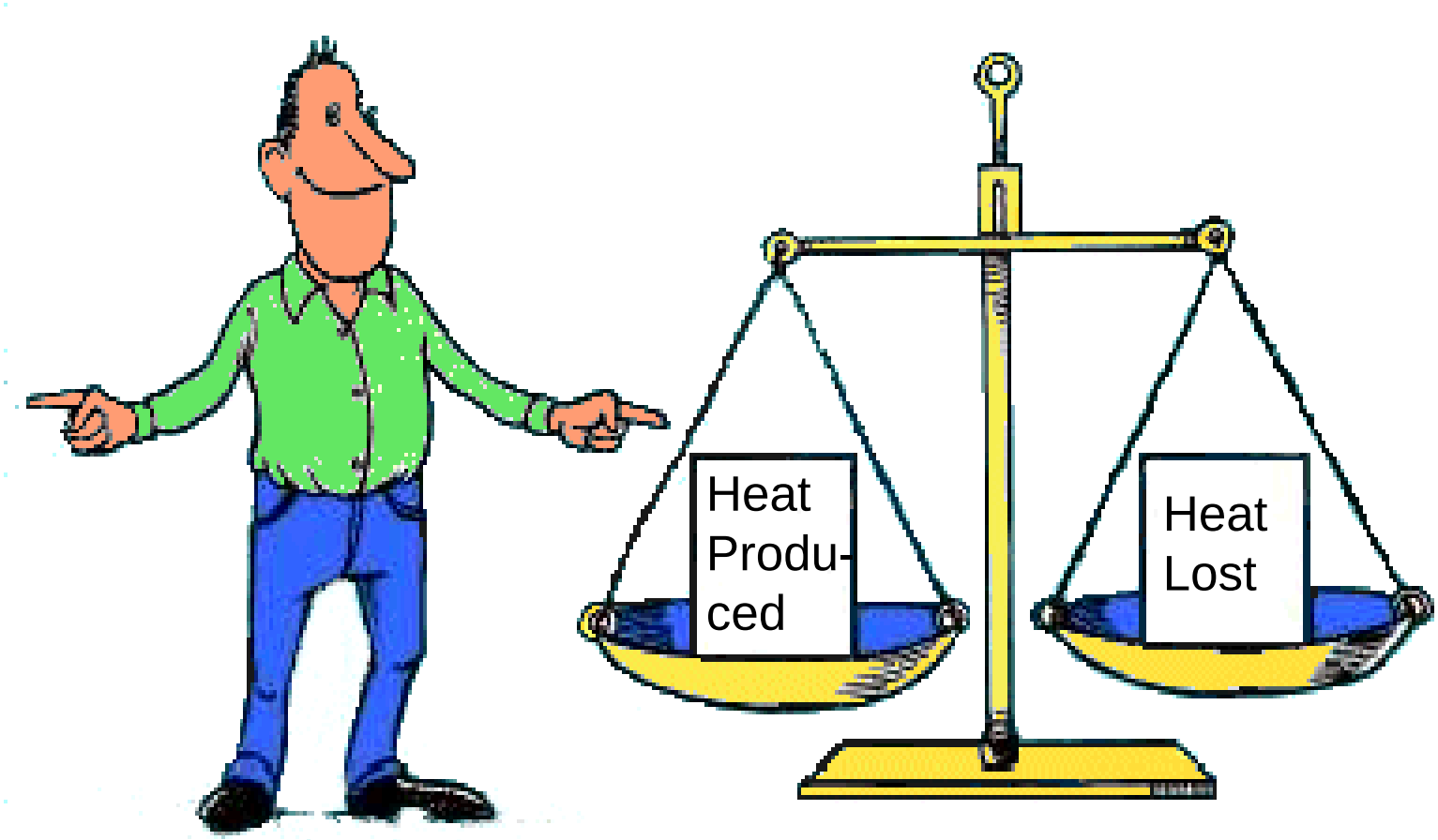
Warm impulses

Cold impulses

Activity

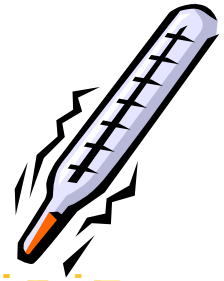
- Heat sensor in Hypothalamus send impulses when temperature exceeds 37 ºC.
- Cold sensors sends impulses when skin temperature below 34 ºC.
- The bigger temperature difference, the more impulses.
- If impulses are of same magnitude, you feel thermally neutral.
- If not, you feel cold or warm.

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

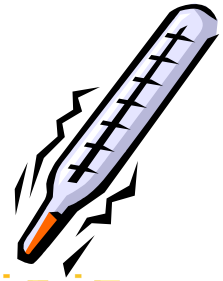
M = metabolic rate

W = mechanical work done by human body

E = rate of total evaporation loss

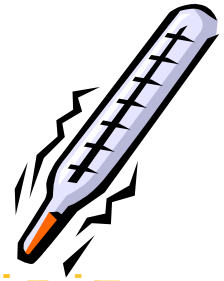
R + C = dry heat exchange through radiation & convection

Heat Balance Equation



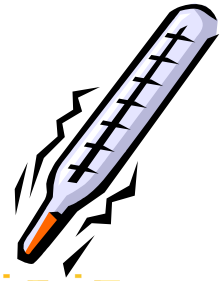
- Rate of heat storage, S
  - proportional to rate of change in mean body temp.
  - normally, S is zero; adjusted by the thermo-regulatory system of the body
- Metabolic rate, M
  - heat released from human body per unit skin area
    - depends on muscular activities, environment, body sizes, etc.; unit 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



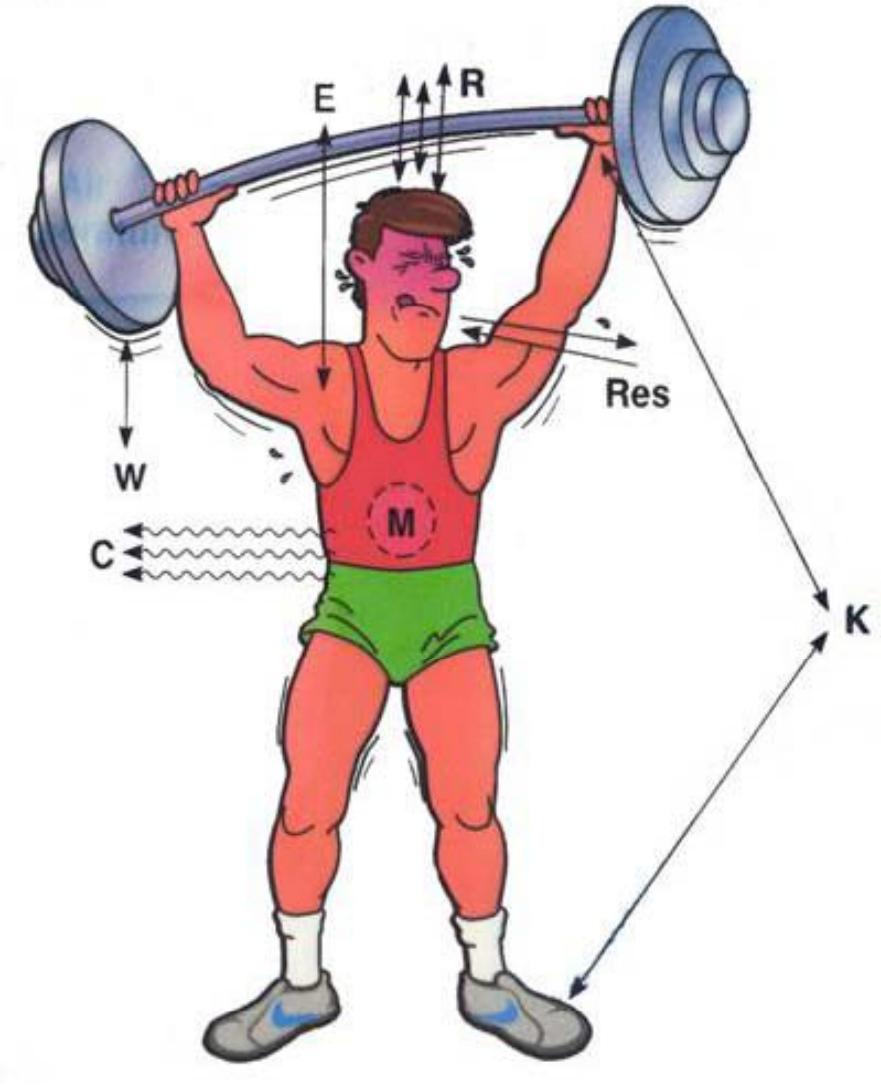
- Mechanical work, W
  - energy in human body transformed into external mechanical work
- Evaporative heat loss, E
  - release of latent heat energy from evaporation of body fluid
    - respired vapour loss, E_{res} (respiration heat losses: latent E_{rel} and sensible E_{rec})
    - evaporative heat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

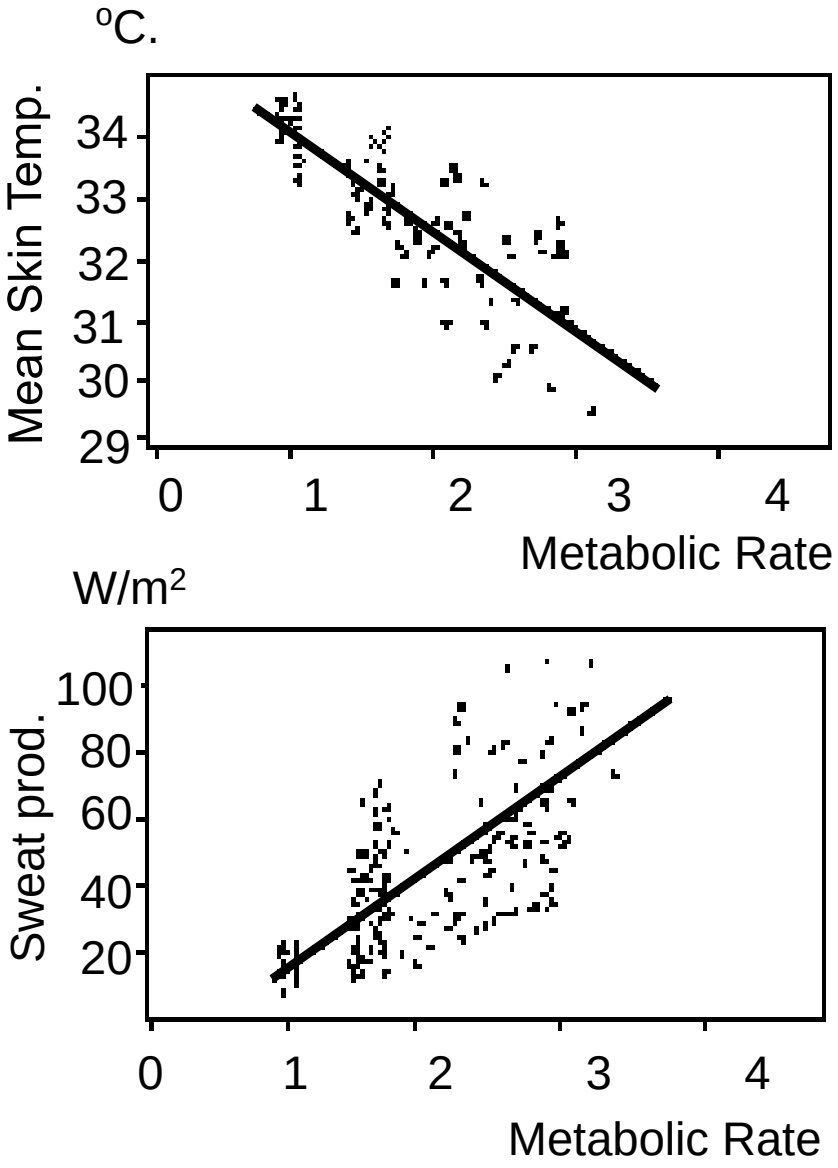


- The dry heat loss (R+C) represents ~70% at low Clo-values and ~60% at higher Clo-values

- 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)

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. (^oC)

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

P_s = water vapour pressure (kPa)

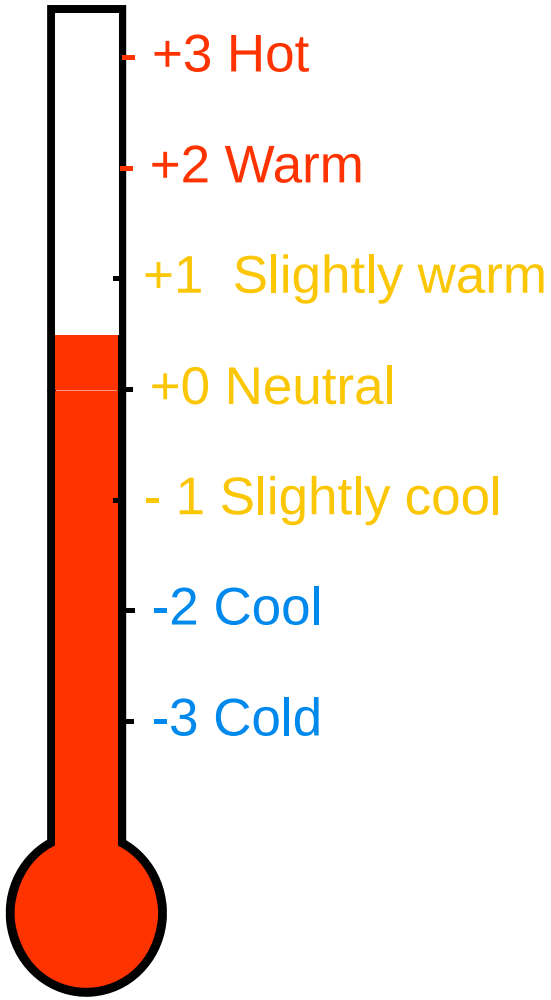
Predication of Thermal Comfort

- 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

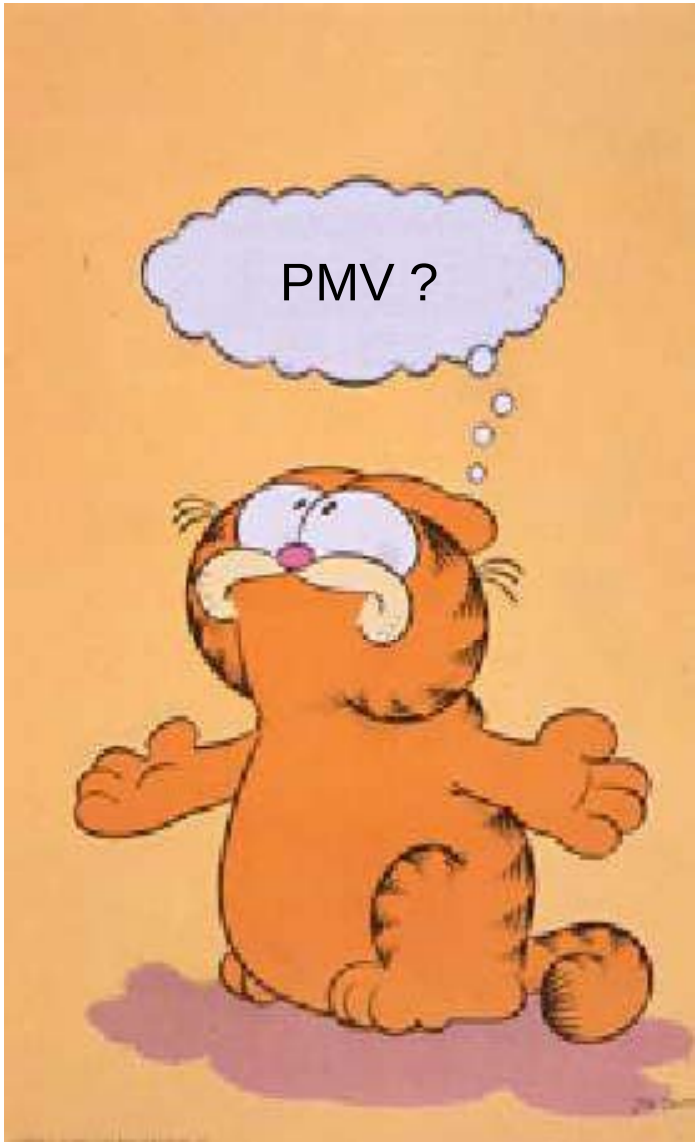
- **PMV**
  - a complex function of six major comfort parameters;
  - predict mean value of the subjective ratings of a group of people in a given environment
- **PPD**
  - determined from PMV as a quantitative measure of thermal comfort
  - ‘dissatisfied’ means not voting -1, +1 or 0 in PMV
  - normally,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



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

$$\Longrightarrow$$

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

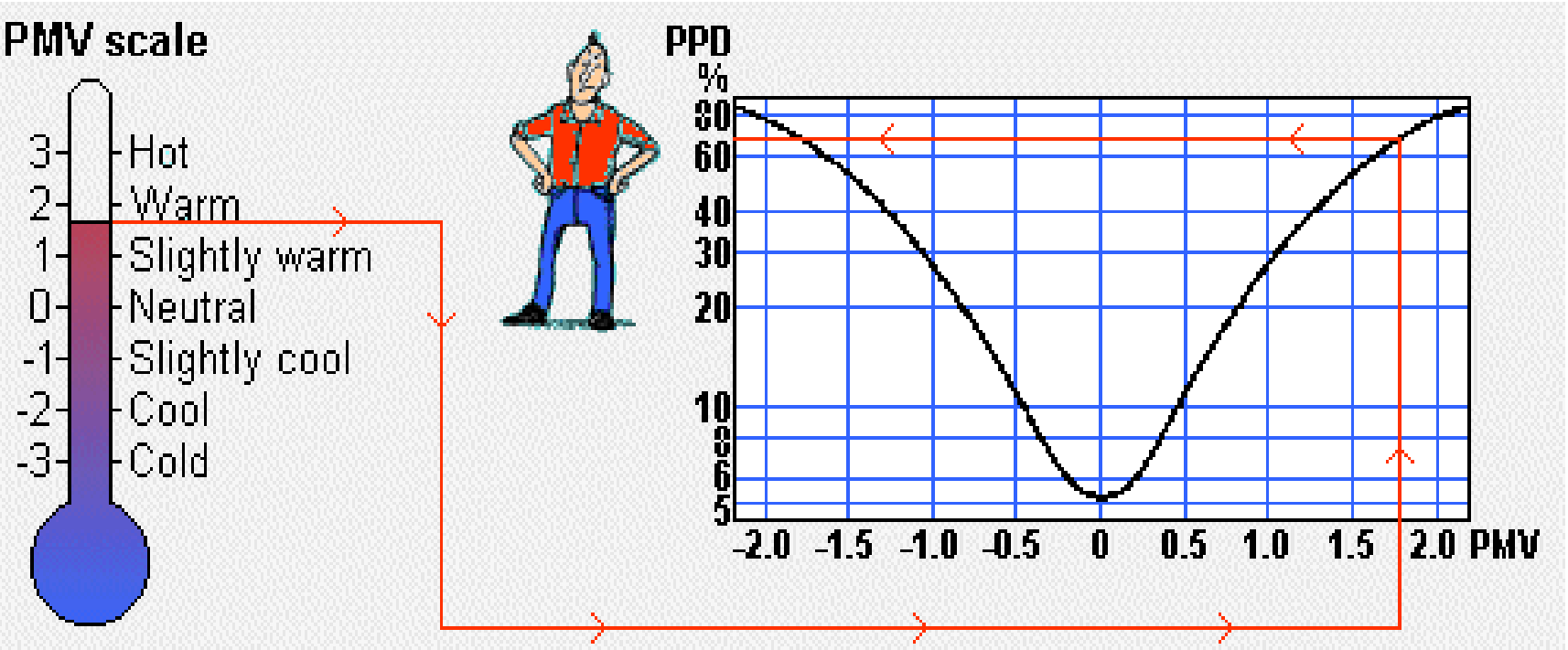
$$h_{c,eq} = 2{,}38*(t_{cl} - t_{eq})^{0{,}25}$$

$$f_{cl}\begin{cases}1{,}00+0{,}2*I_{cl} \text{ for } I_{cl}<0{,}5 \text{ clo}\\ 1{,}05+0{,}1*I_{cl} \text{ for } I_{cl}>0{,}5 \text{ clo}\end{cases}$$

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.

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

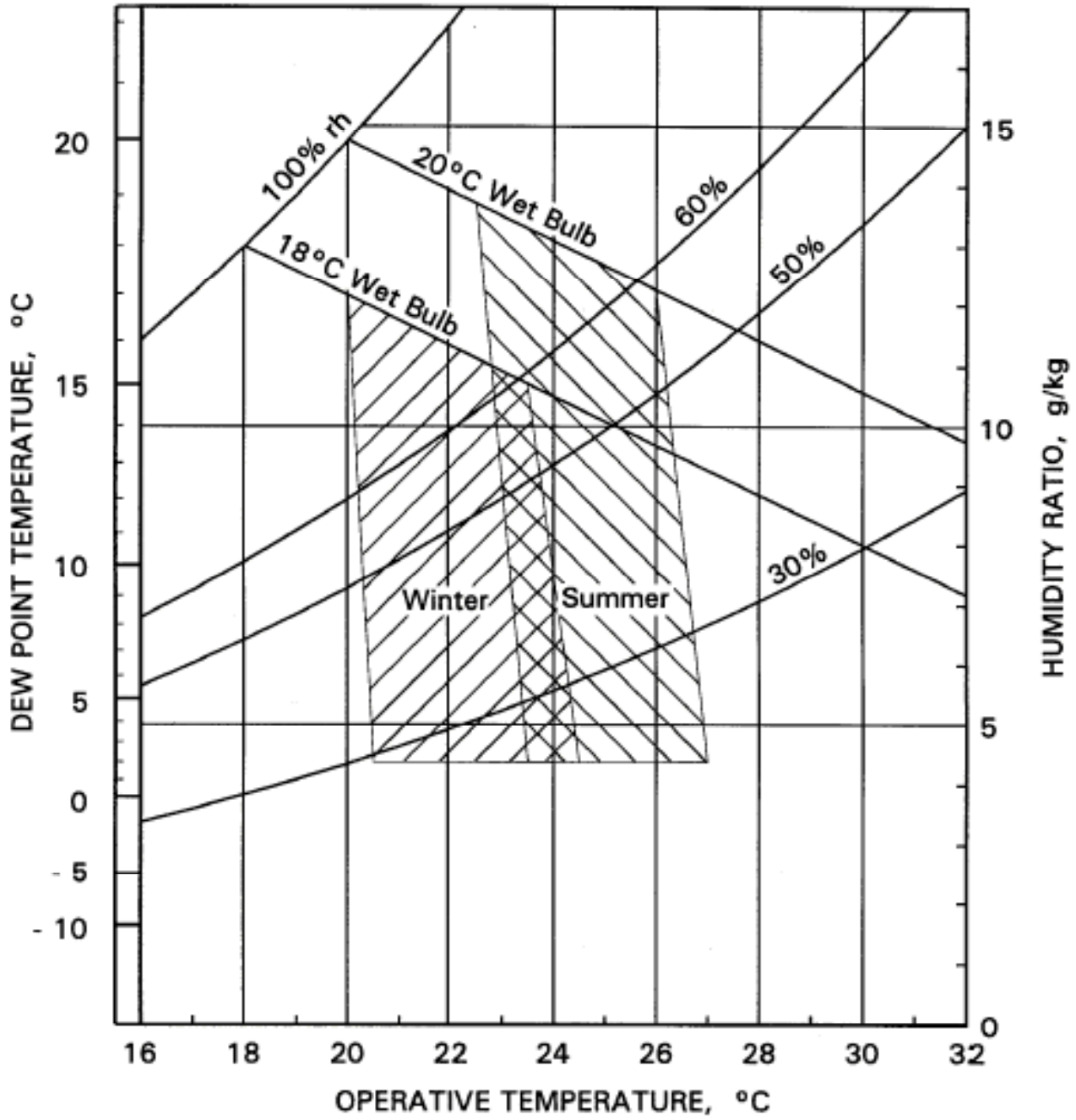
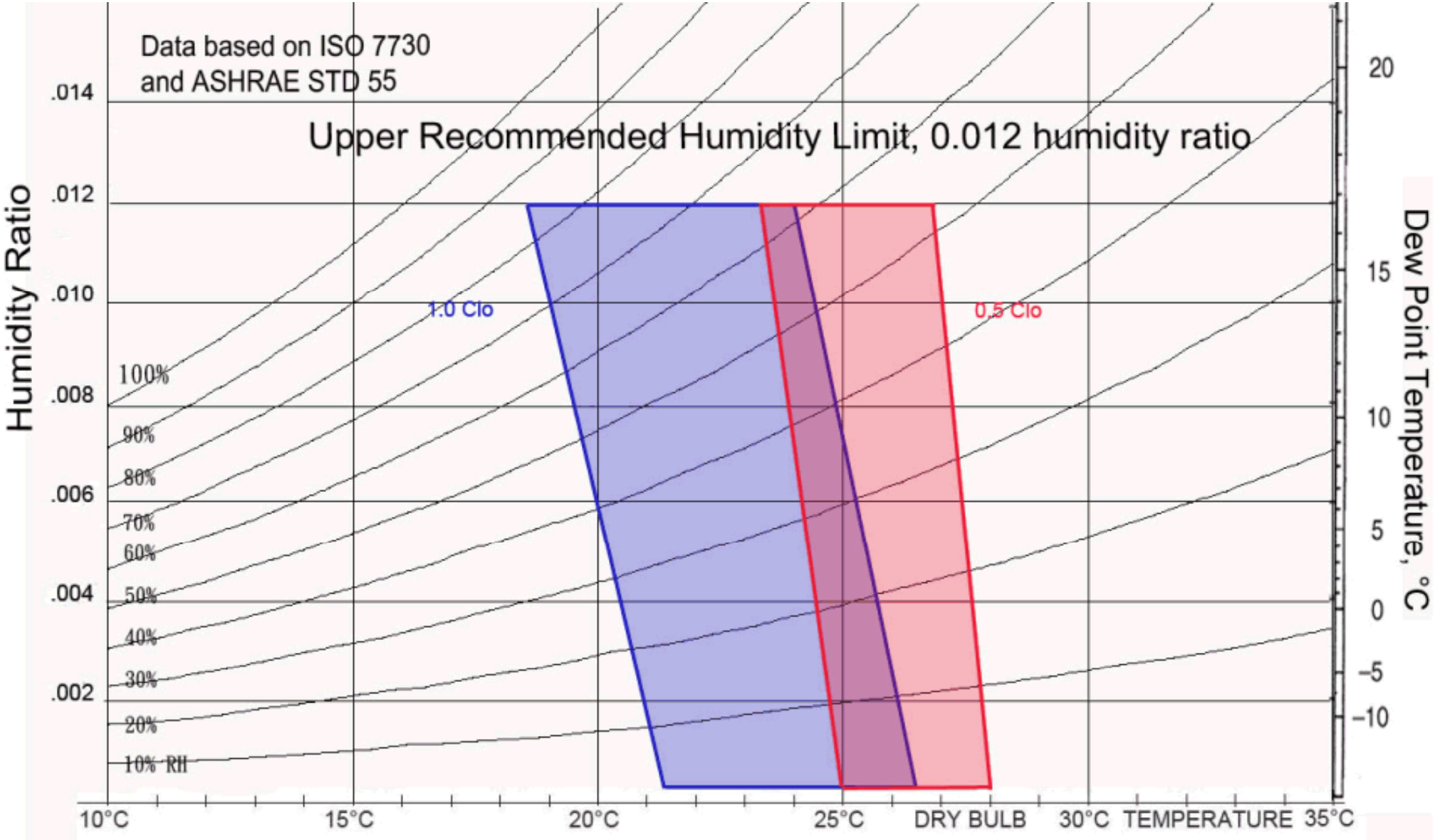


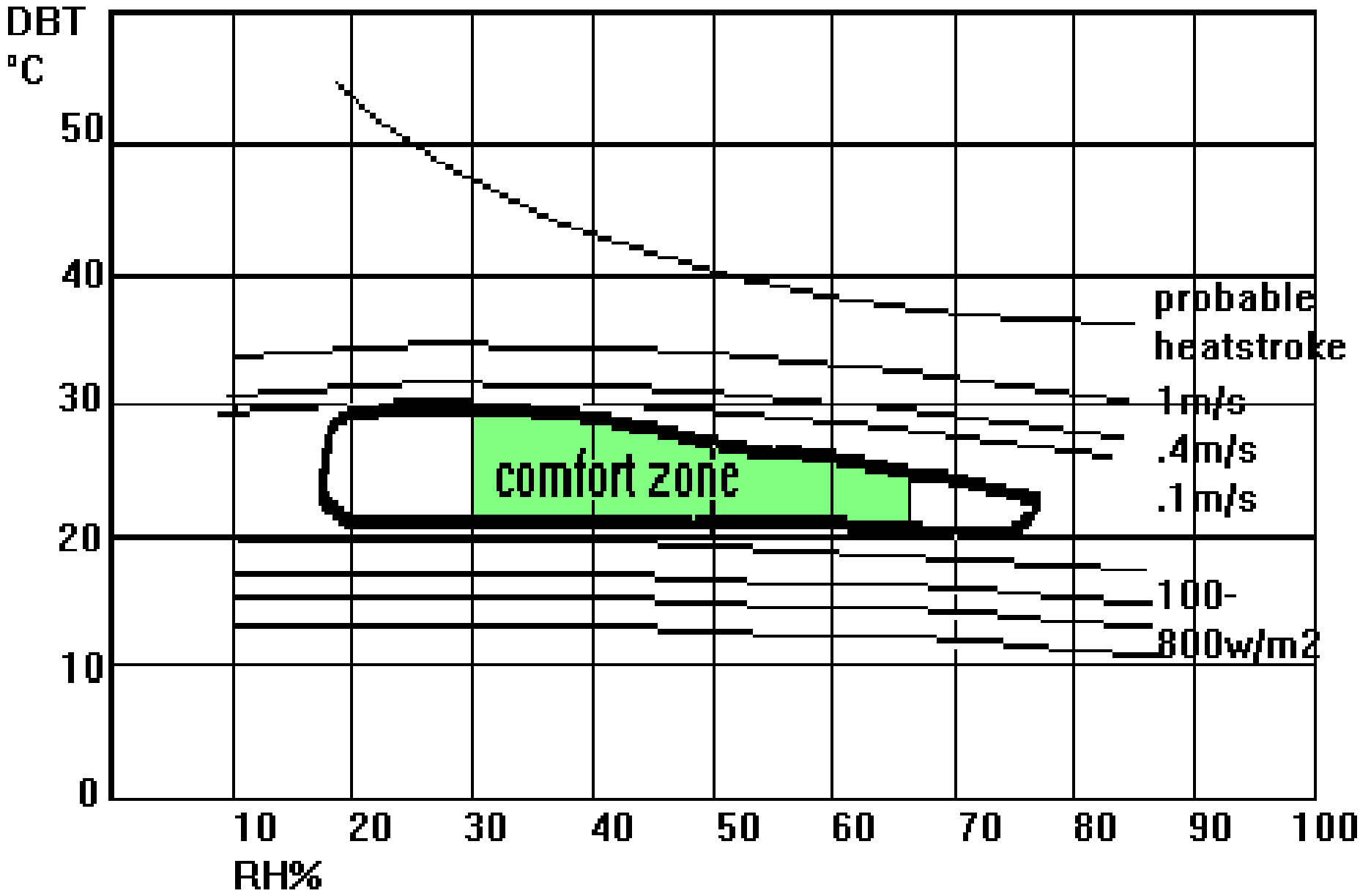
Fig. 5 ASHRAE Summer and Winter Comfort Zones

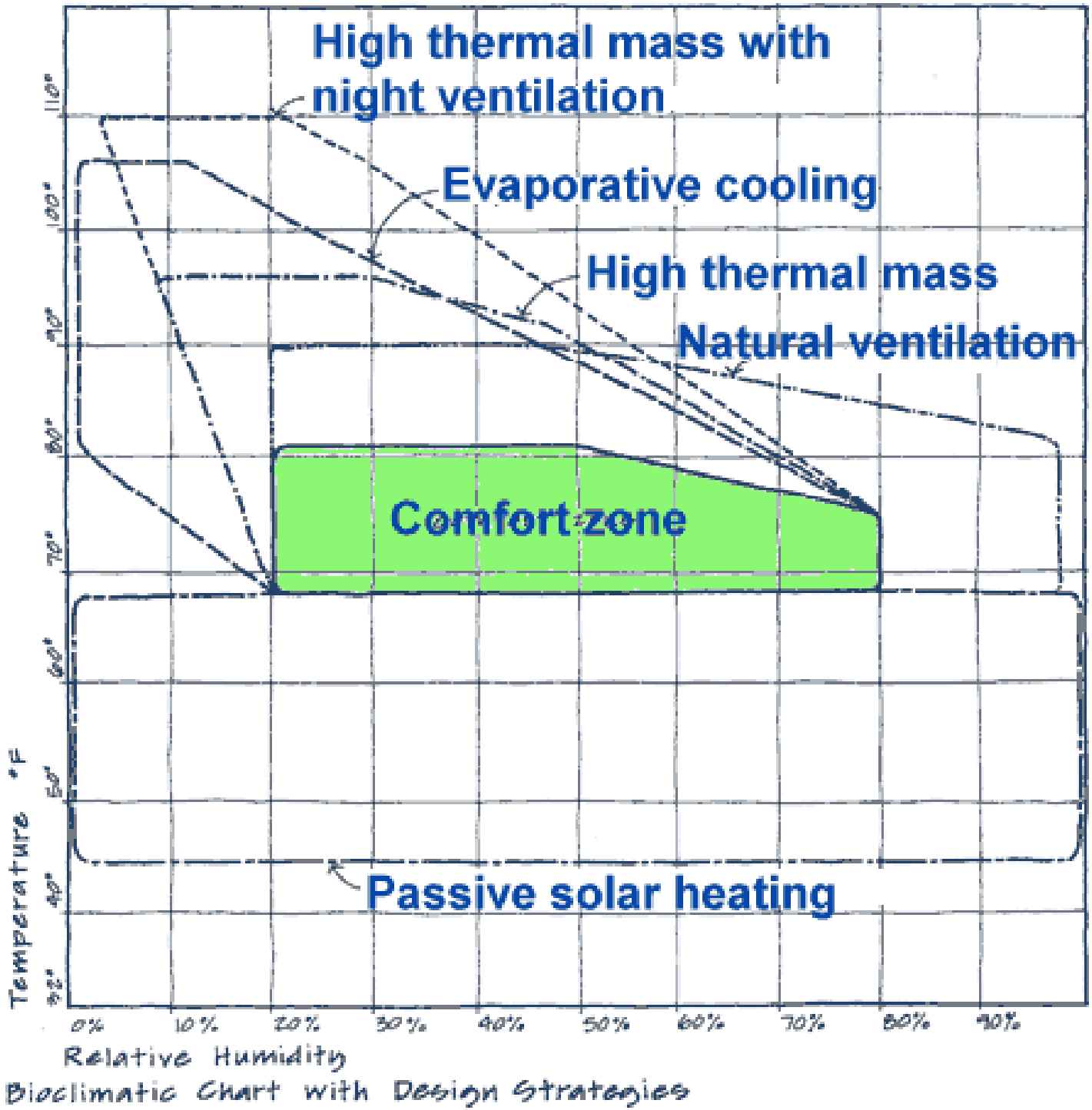
(Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during primarily sedentary activity.)

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



Olgyays bioclimatic chart





Bioclimatic Chart with Design Strategies

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

Influencing Factors

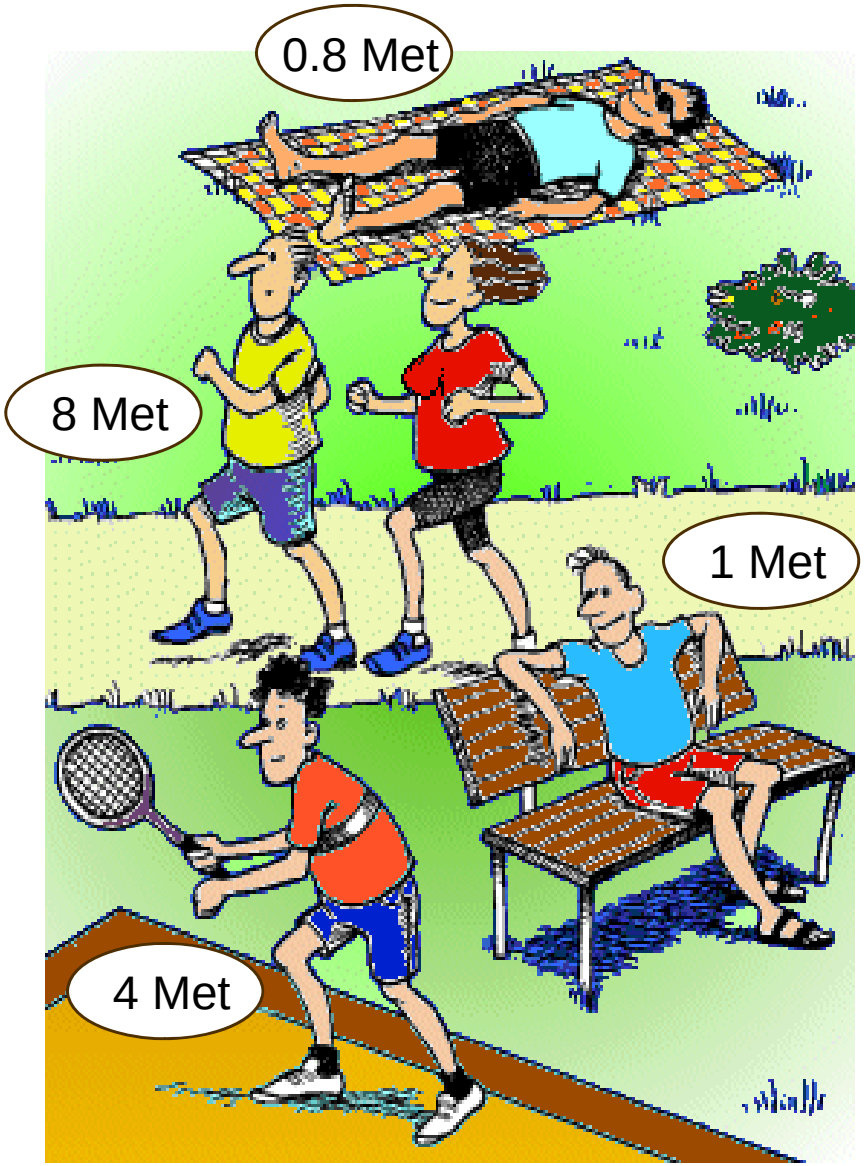
- Other factors affecting comfort:
  - Age
    - Sensation of old people and younger people
  - Adaptation
    - People in warm climates may adapt to hot environment
  - Sex
    - Women: lower skin temp., evap loss & lower met. rate
    - Clothing and perferrence of temp.

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.

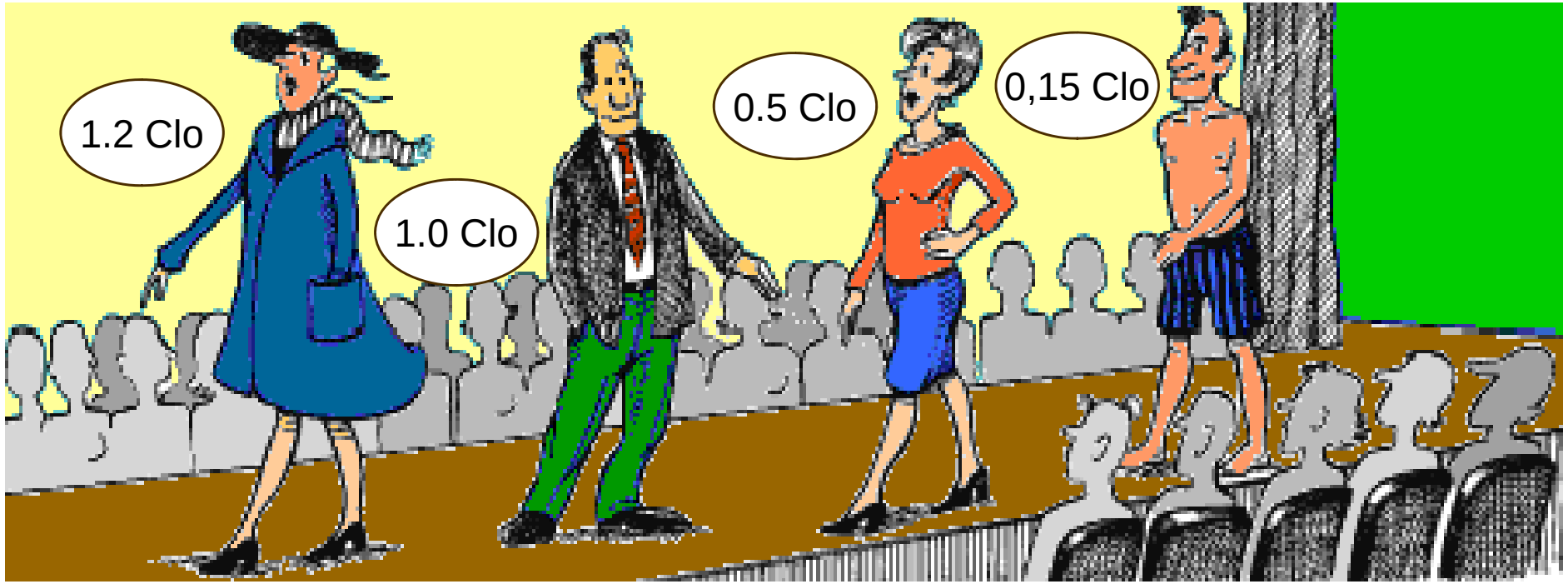
Met Value Table

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

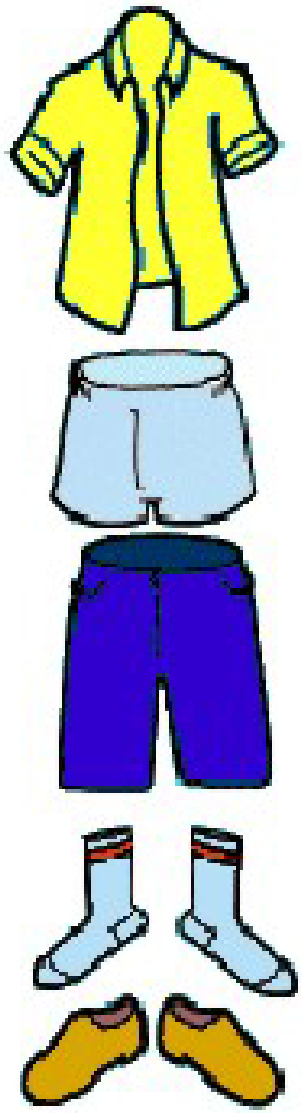
Garment description		**I_{clu} Clo**	**I_{clu} m^2 ∘C/W**
Underwear	Pantyhose	0.02	0.003
	Briefs	0.04	0.006
	Pants long legs	0.10	0.016
Underwear, shirts	Bra	0.01	0.002
	T-shirt	0.09	0.014
	Half-slip, nylon	0.14	0.022
Shirts	Tube top	0.06	0.009
	Short sleeves	0.09	0.029
	Normal, long sleeves	0.25	0.039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

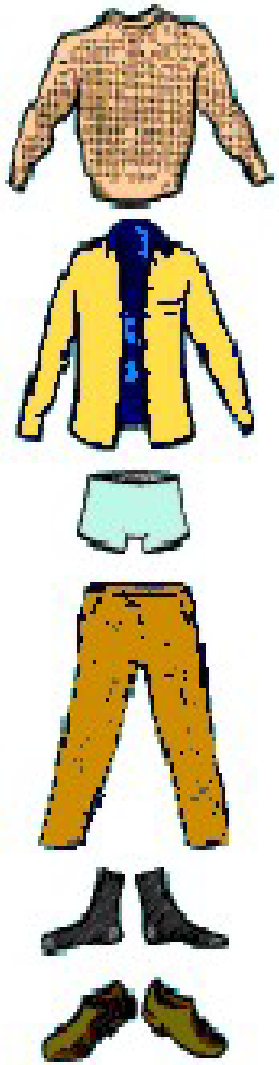
Garment description		**I_{clu} Clo**	**I_{clu} m^2 ◦C/W**
Jackets	Vest	0.13	0.020
	Jacket	0.35	0.054
Coats over-trousers	Coat	0.60	0.093
	Parka	0.70	0.109
	Overalls	0.52	0.081
Sundries	Socks	0.02	0.003
	Shoes (thin soled)	0.02	0.003
	Boots	0.10	0.016
	Gloves	0.05	0.008
Skirt, dresses	Light skirt, 15cm 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



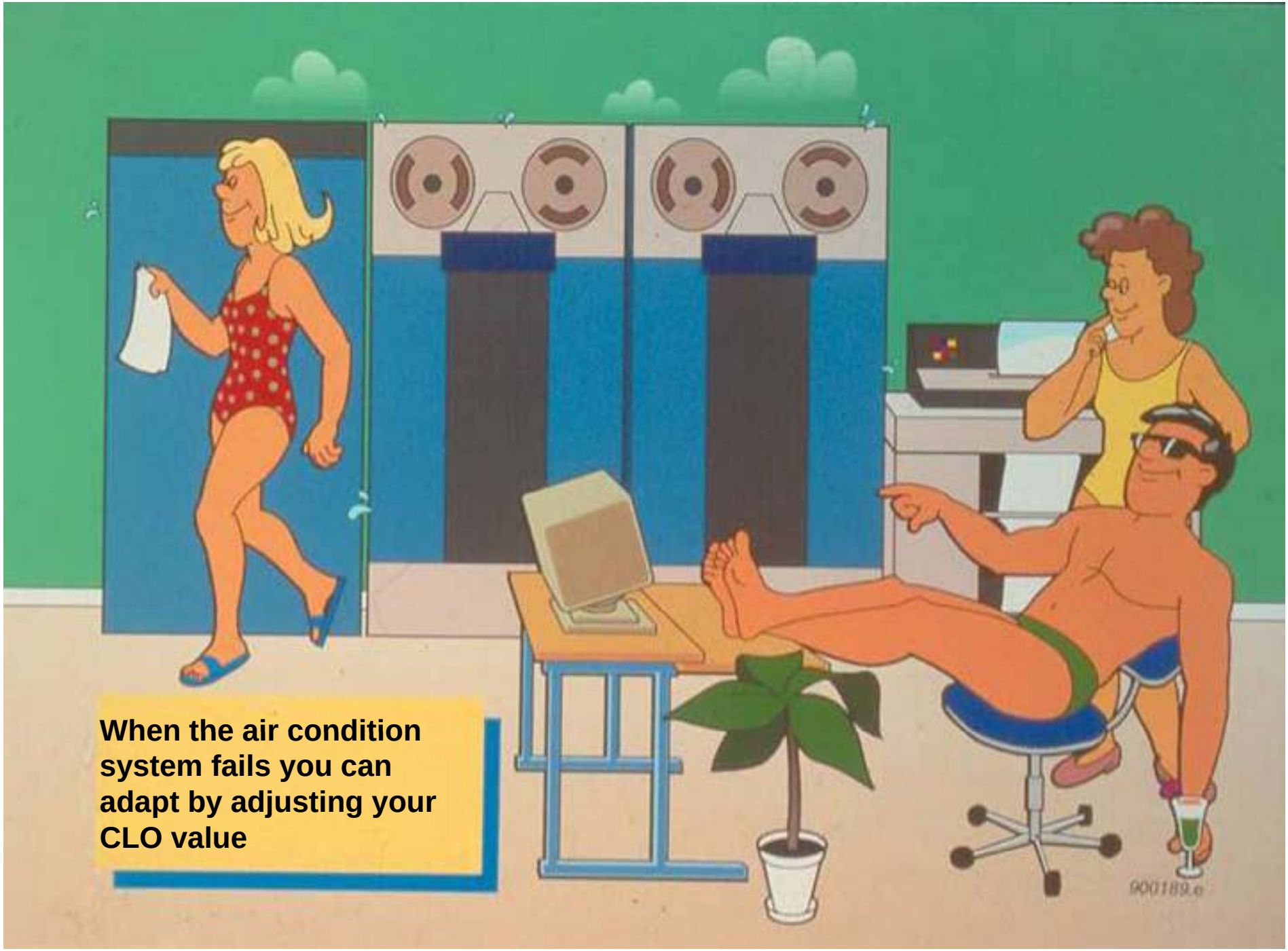
0.28
+
0.25
+
0.04
+
0.25
+
0.05
+
0.04
0.91

Things to consider when calculation the CLO value

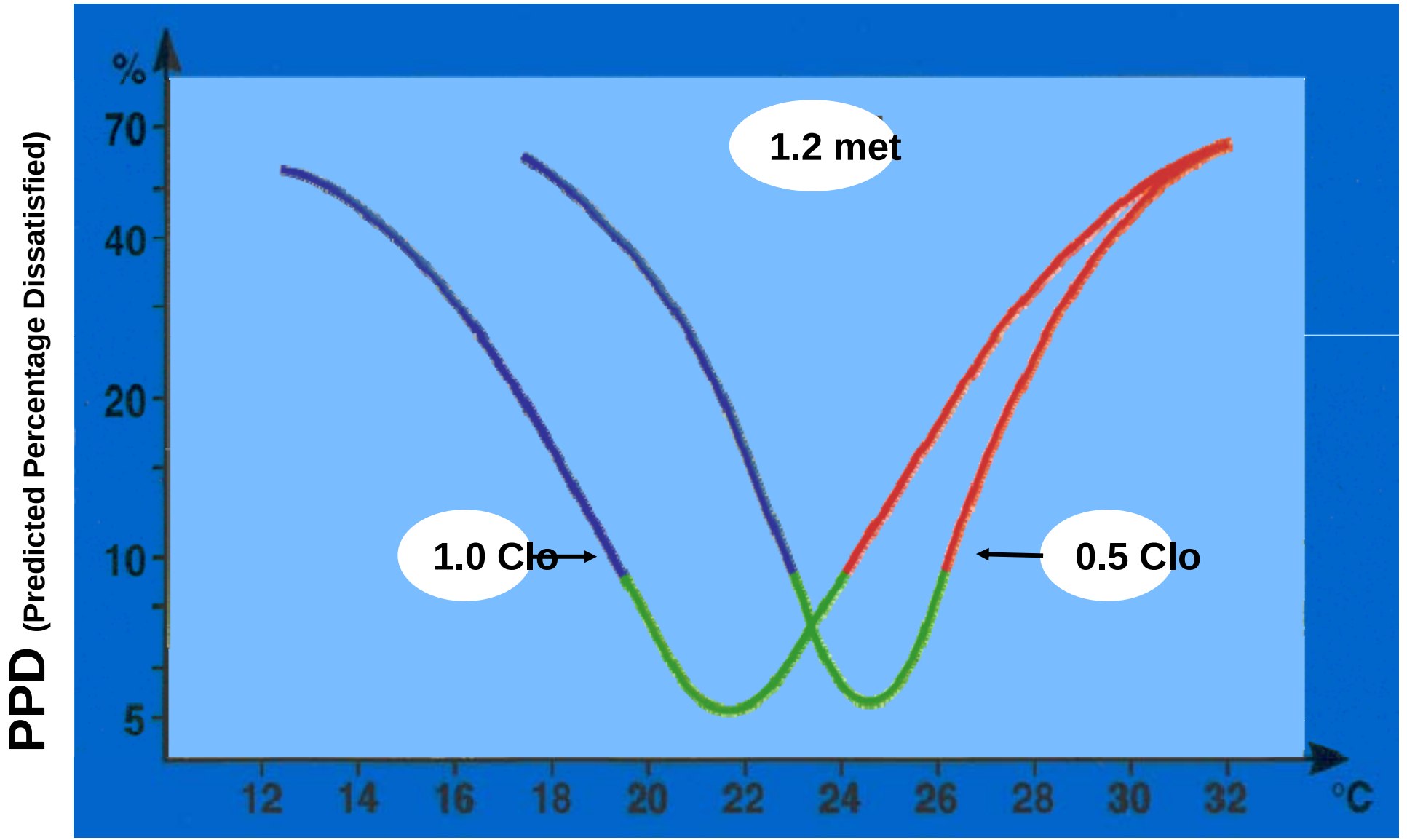
Thermal insulation of chairs

Insulation of wet clothing

Acclimatisation/Adaptation!



Adjustment of Clo Value

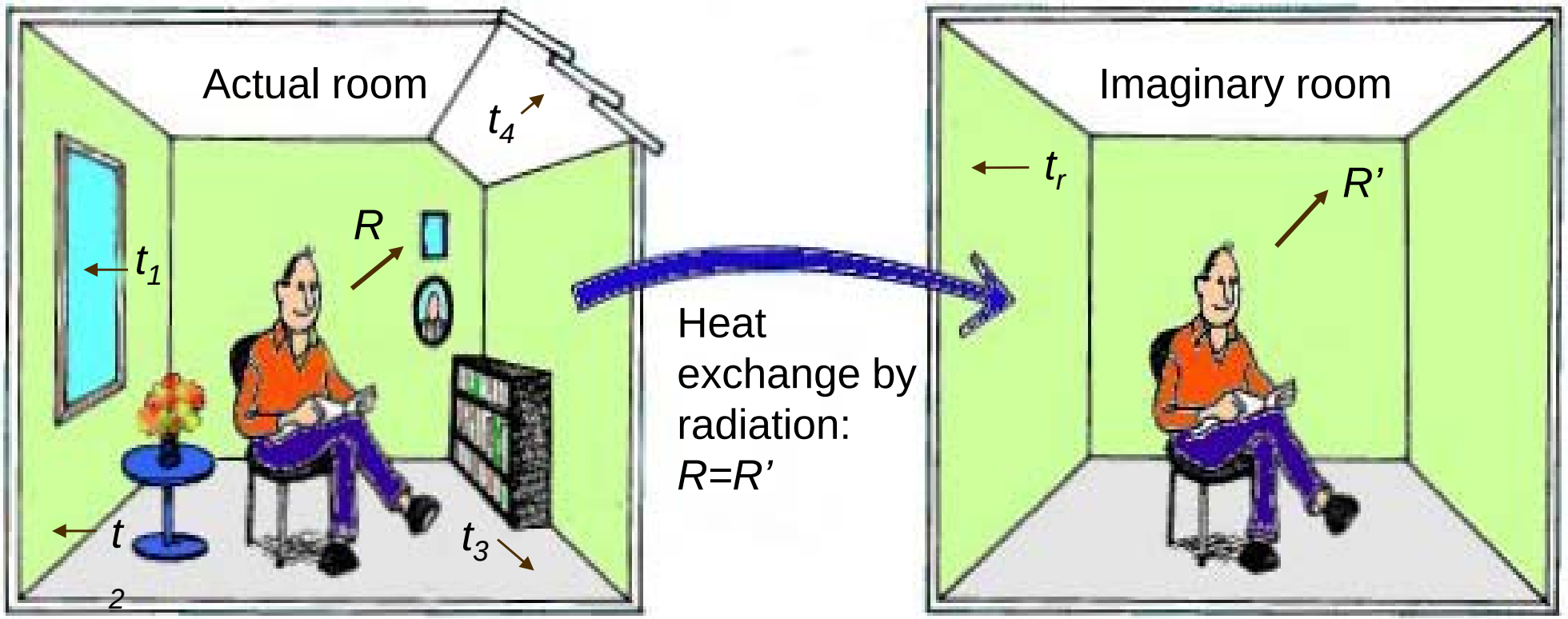


What should be measured?

- 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

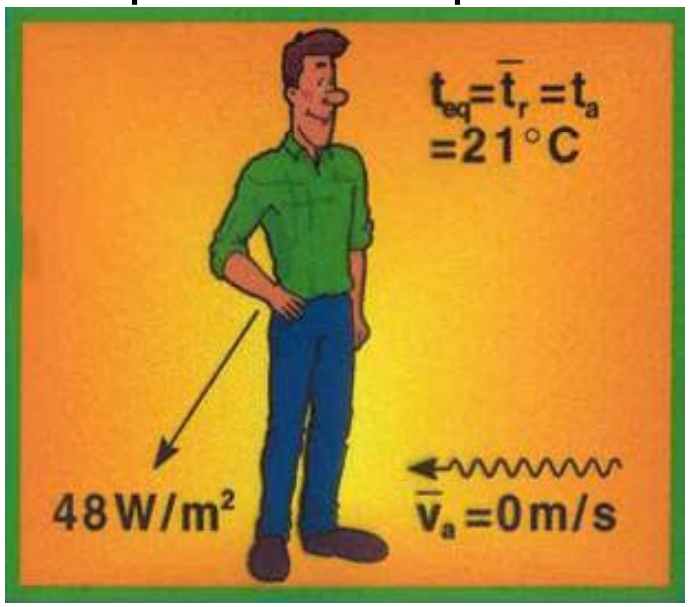
- **Effective temperature, *ET***
  - Temp. of a still, saturated atmosphere, which would in the absence of radiation, produce the same effect as the atmosphere in question (thus, it combines dry bulb temp. and humidity)
  - Represented by a set of equal comfort lines drawn on the psych chart (see ASHRAE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

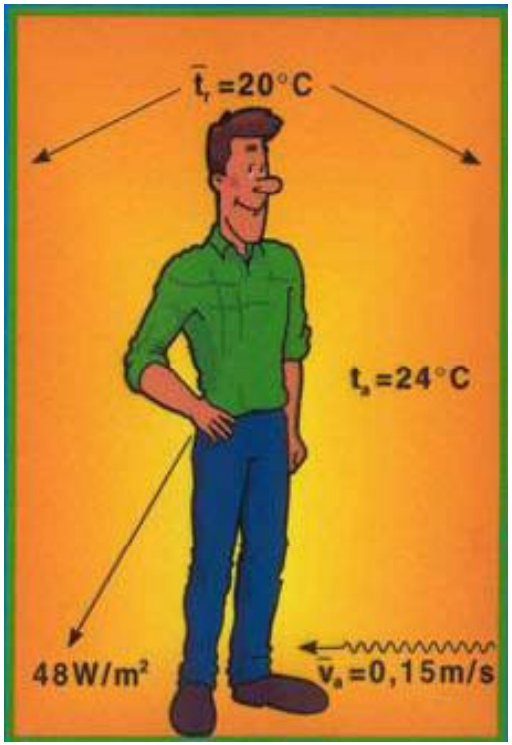
Environmental Indices

- **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



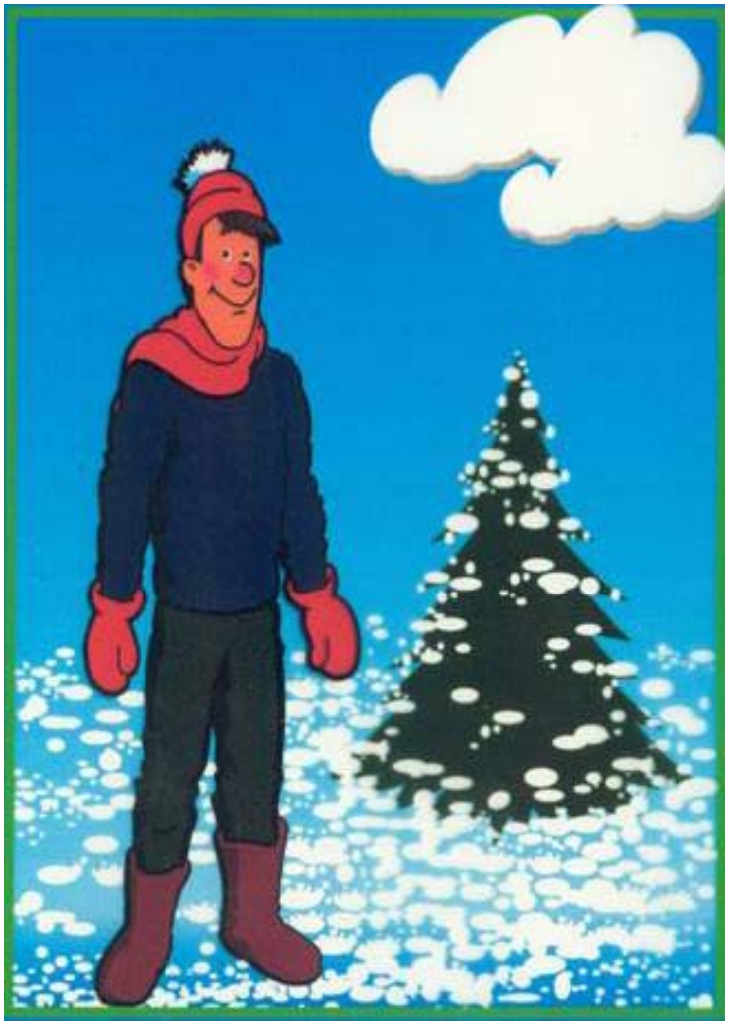


Equivalent temperature

Combines DBT & MRT

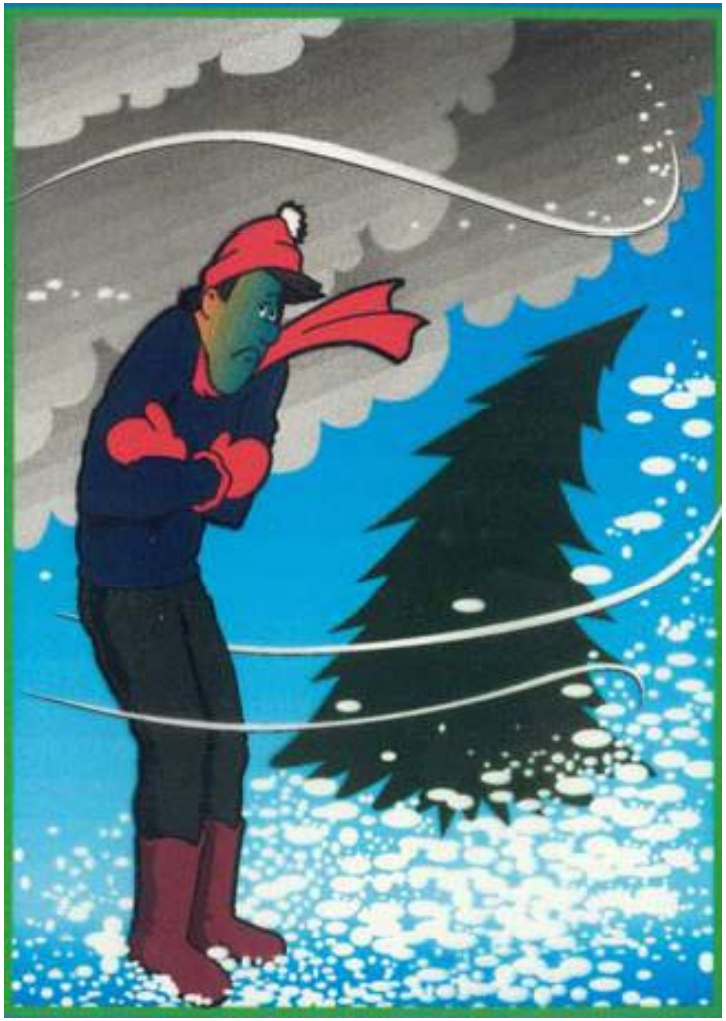
Combines DBT, MRT & air velocity

Operative and Equivalent Temperature



Operative temperature

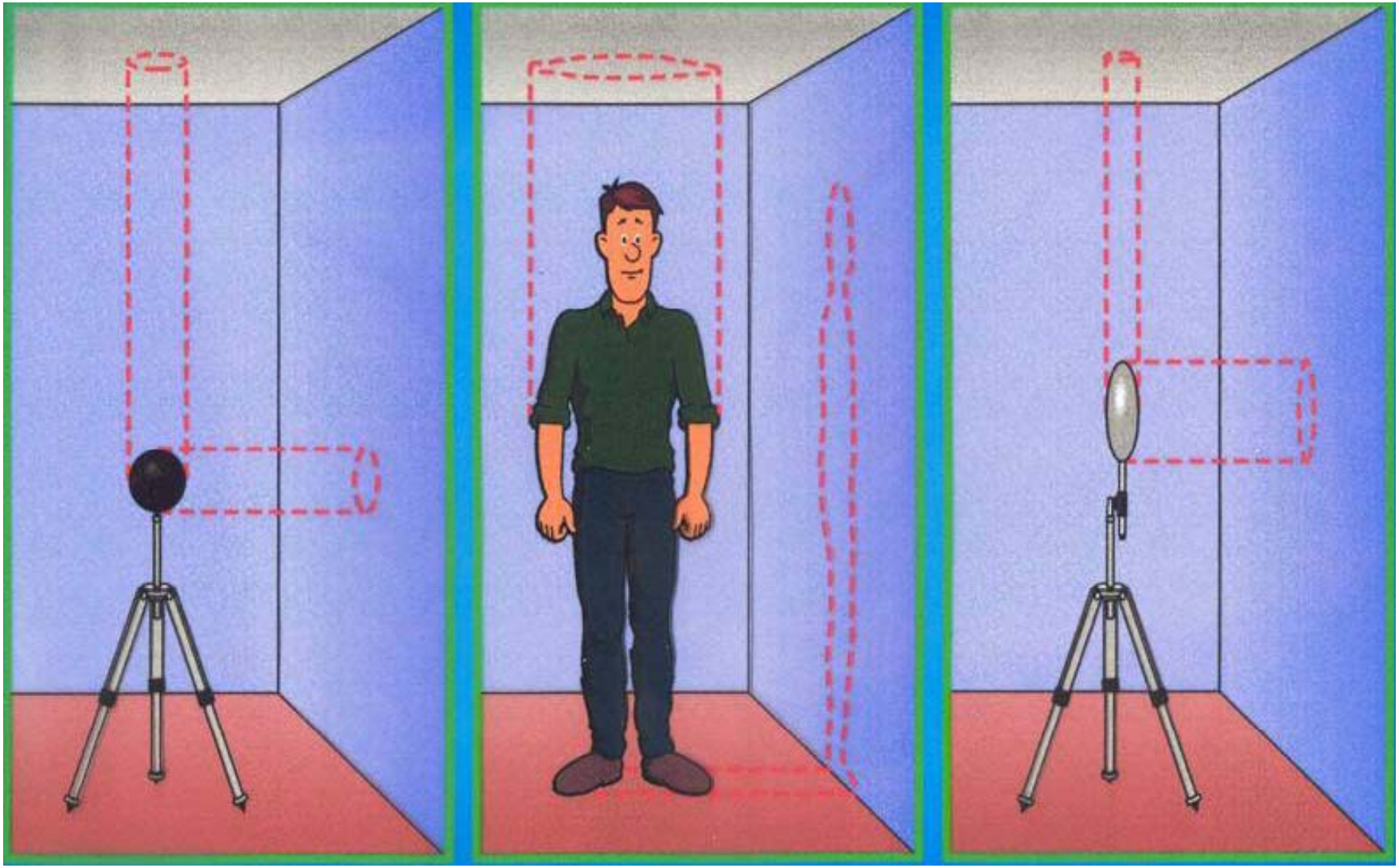
Combines DBT & MRT



Equivalent temperature

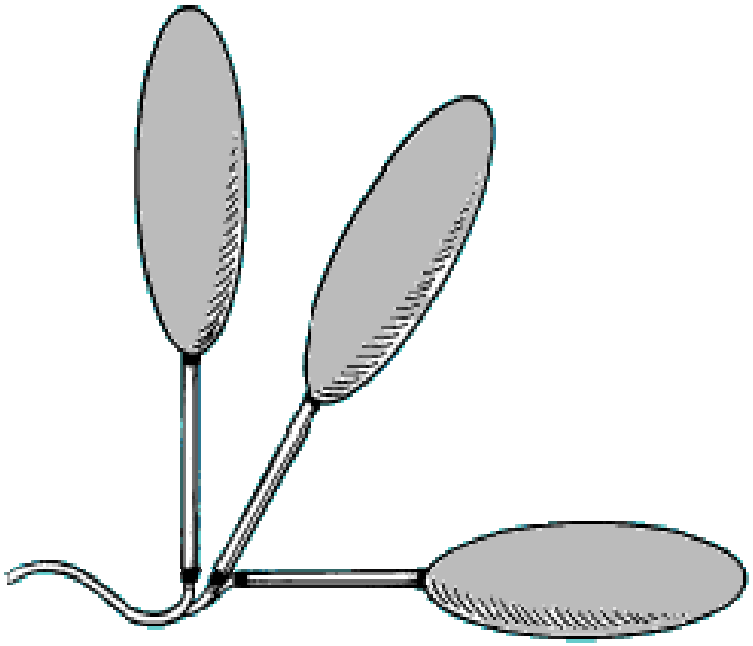
Combines DBT, MRT & air velocity

Projected area factor



$\bar{t}_r$ = 20 °C $\bar{t}_r$ = 20 °C $\bar{t}_r$ = 20 °C

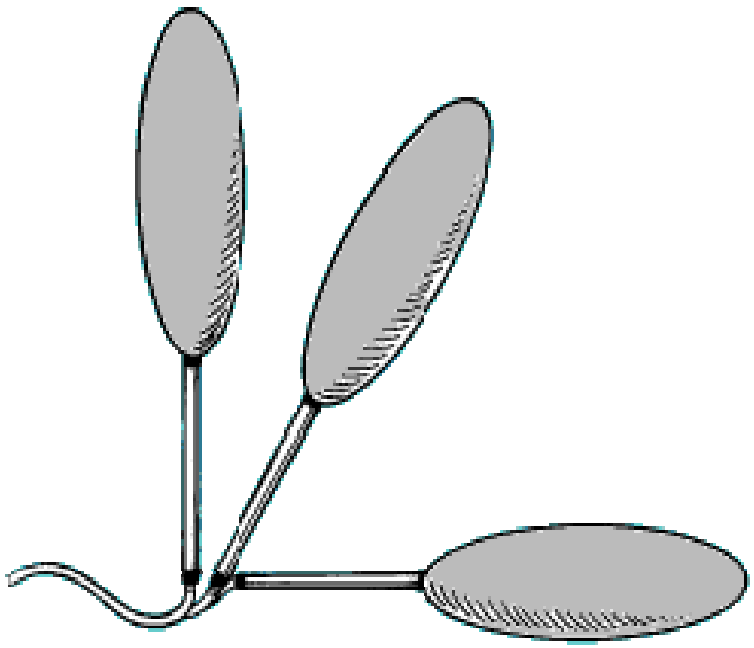
Operative Temperature



- The Operative temperature $\bar{t}_o$ 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

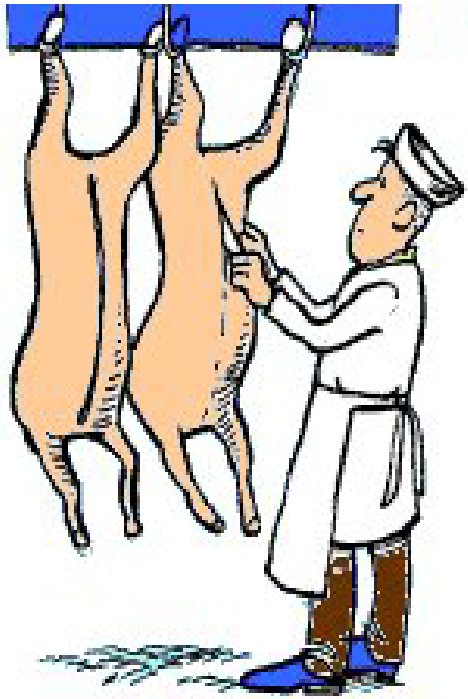


• Dry Heat Loss or equivalent temperature can be measured directly, using a heated Operative Temperature shaped transducer.

•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)

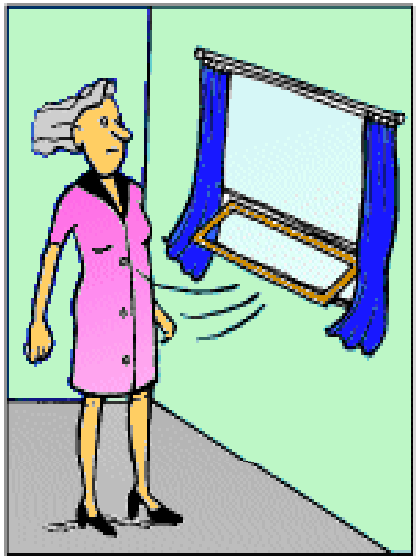


1.7 clo
2.5 Met
RH=50%
t_{co}=6ºC

0.8 clo
2.2 Met
RH=50%
t_{co}=18ºC

0.5 clo
1.2 Met
RH=50%
t_{co}=24,5ºC

Local Thermal Discomfort



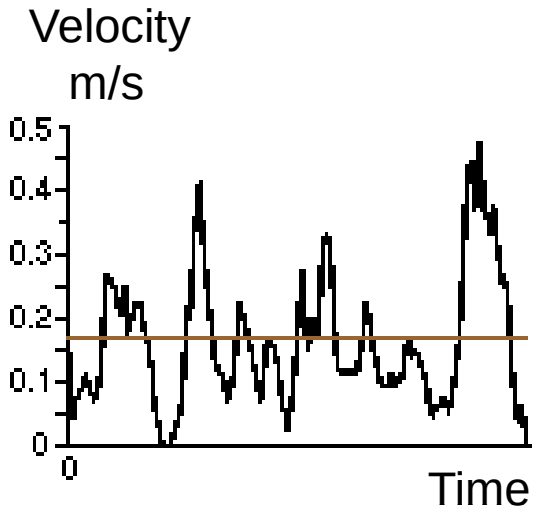
- Draught

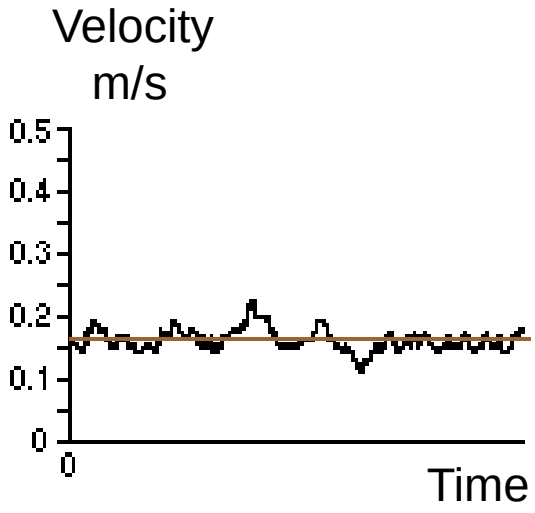
- Radiation Asymmetry

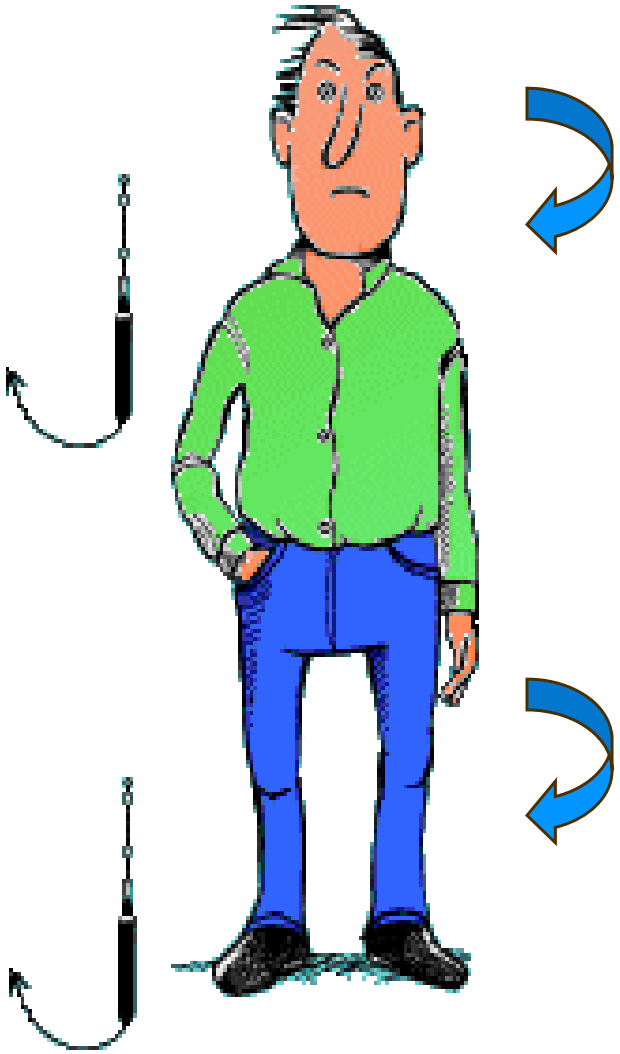
- Vertical Air Temperature Differences.

- Floor temperature

Draught

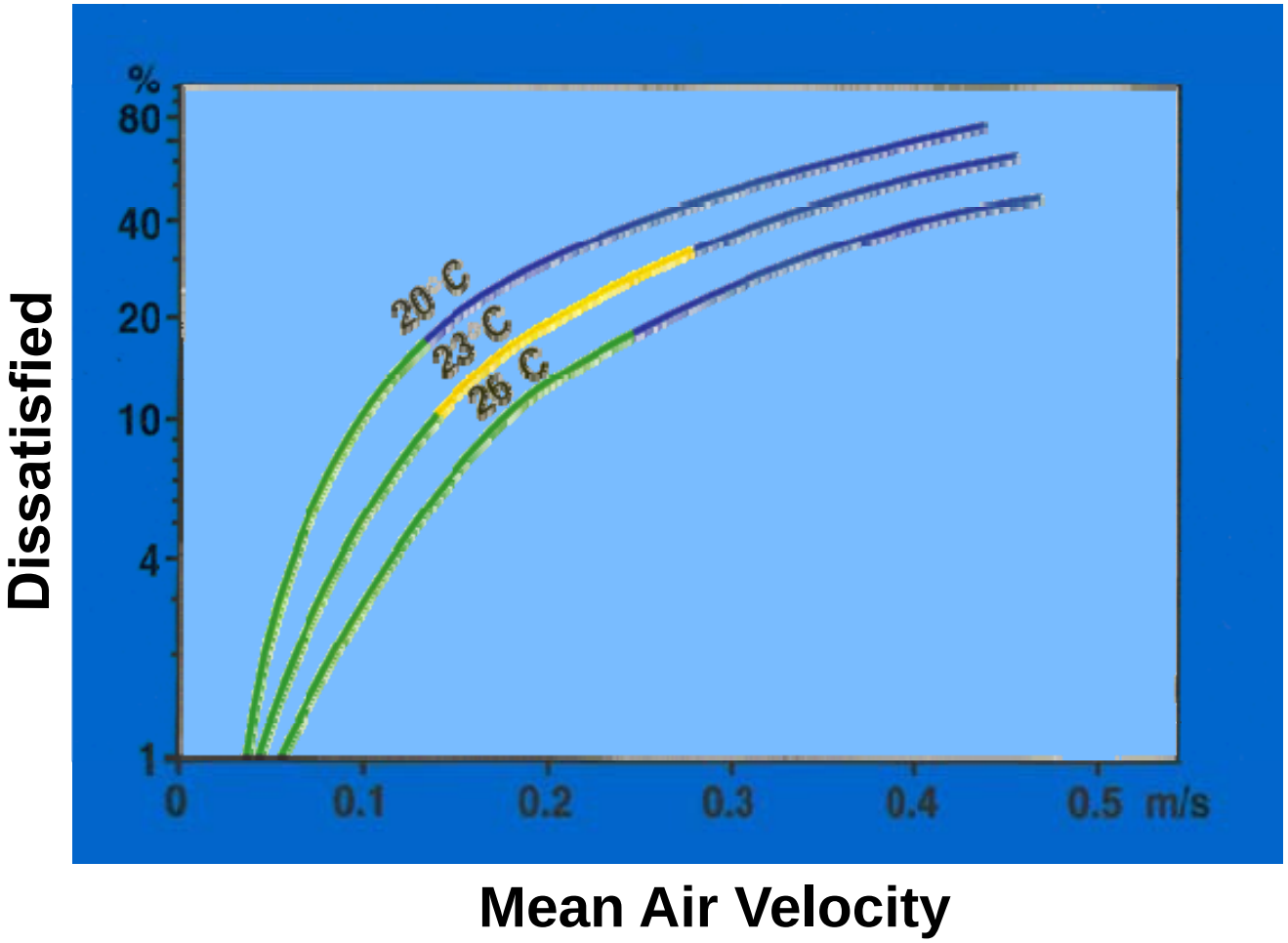






- Draught is the most common complaint indoors
- What is felt is Heat Loss
- Heat Loss is depending on average Air Velocity, Temperature and Turbulence
- High Turbulence is more uncomfortable, even with the same Heat Loss

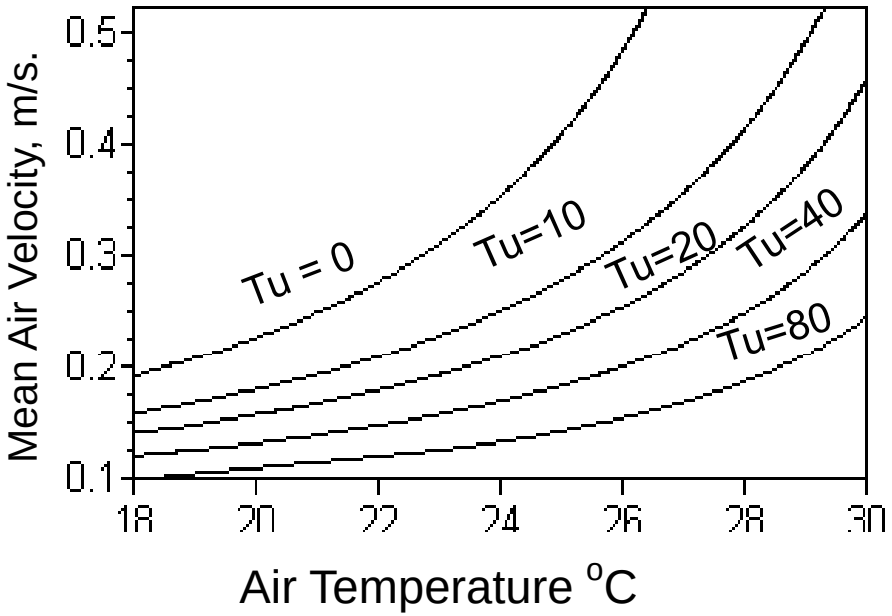
Draught



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

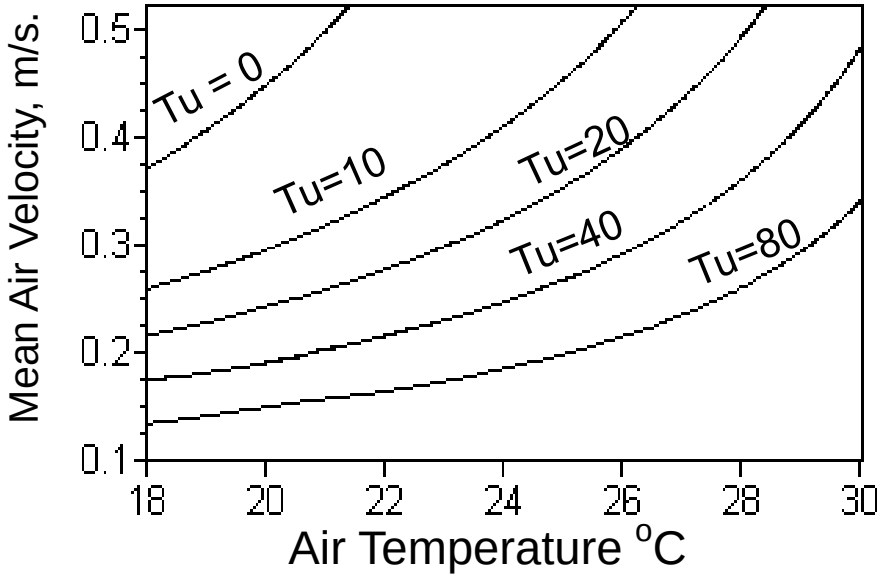
Evaluating Draught Rate

15% dissatisfied

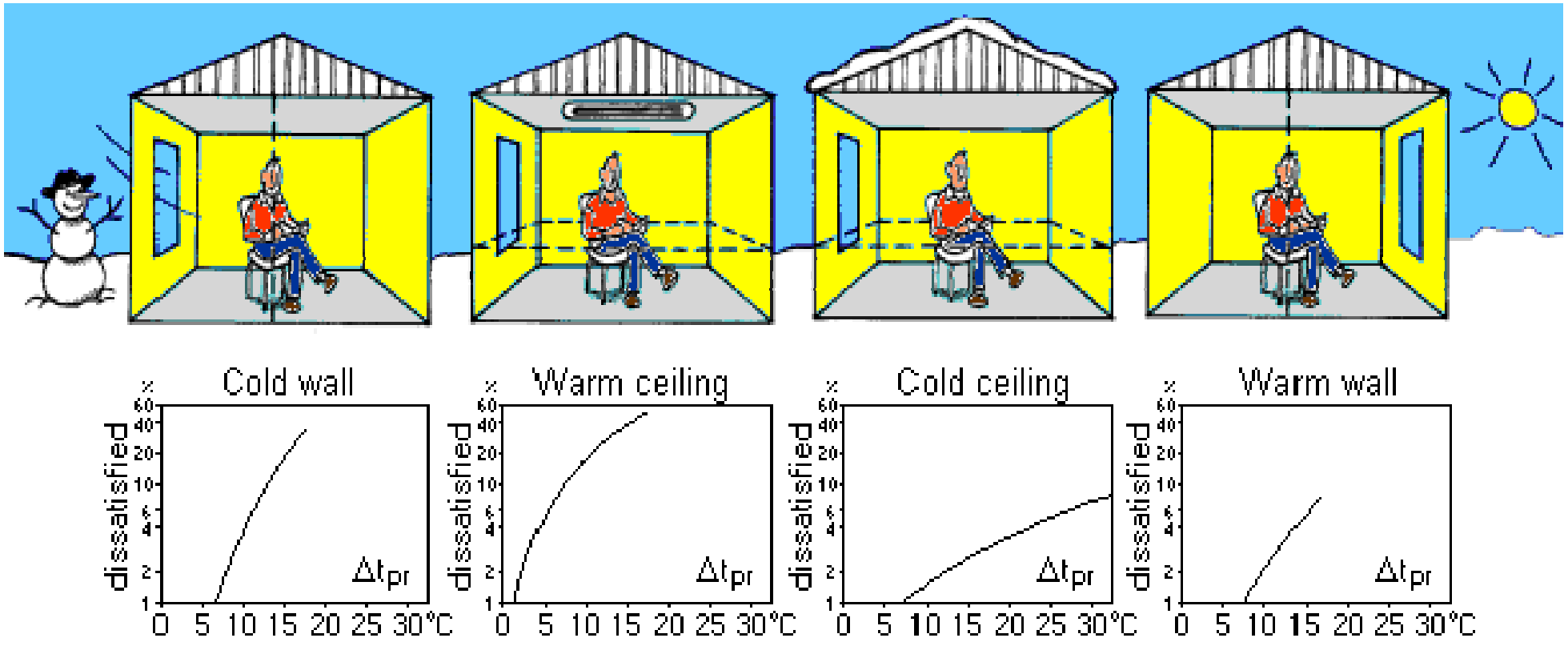


- Fluctuations in Air Velocity is described by Turbulence Intensity (Tu)
- Draught Rate equation is based on studies of 150 people, and stated in ISO 7730

25% dissatisfied

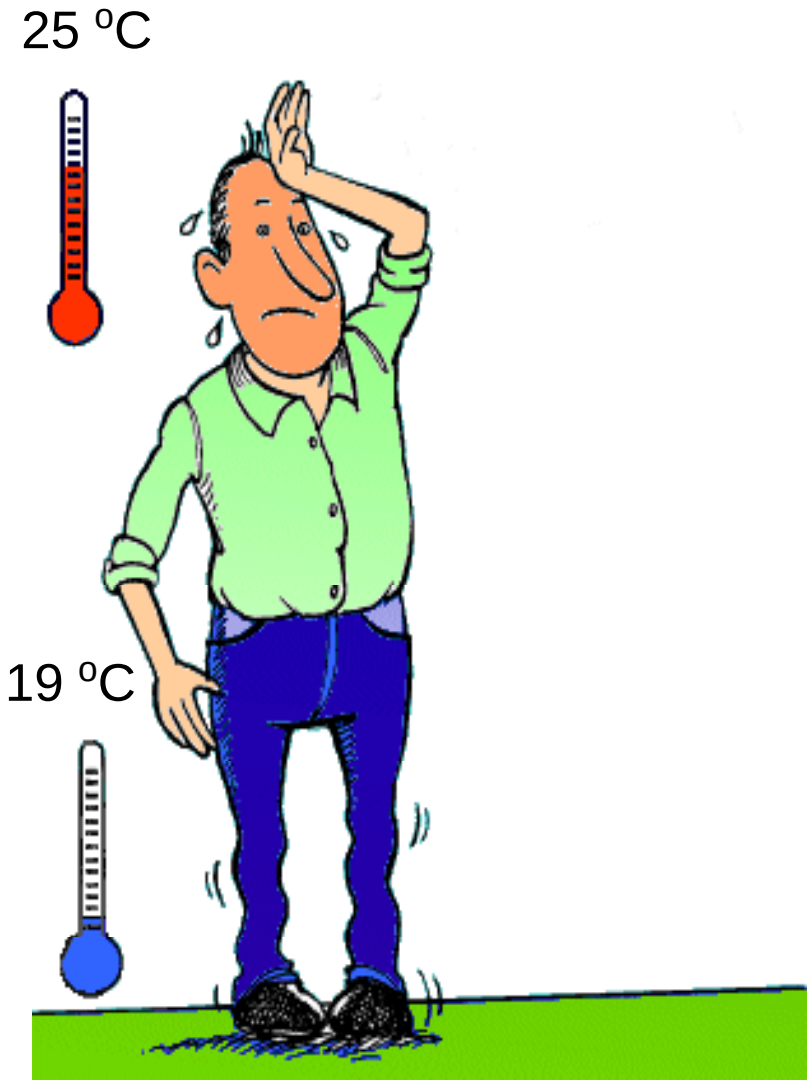


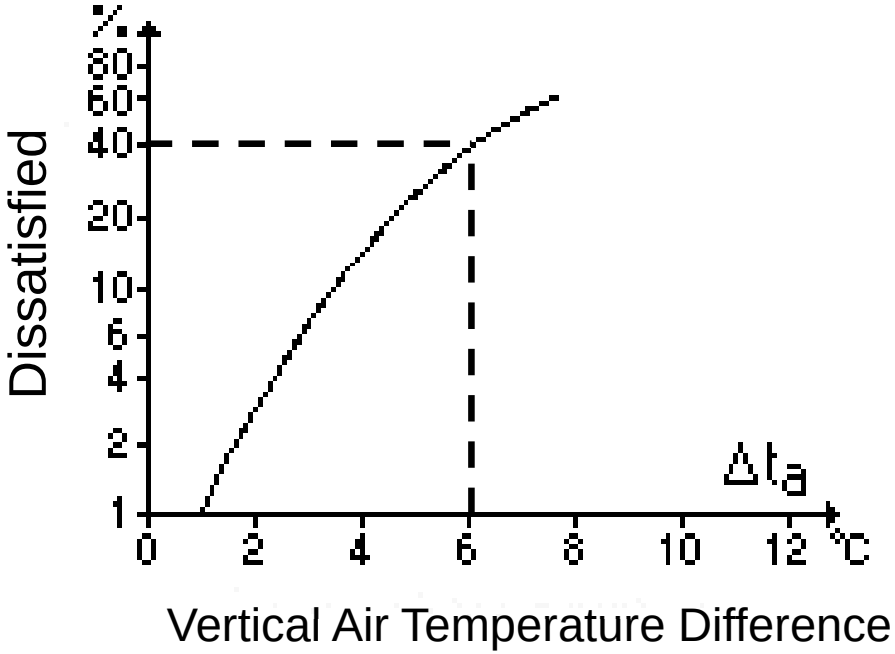
Radiation Asymmetry



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

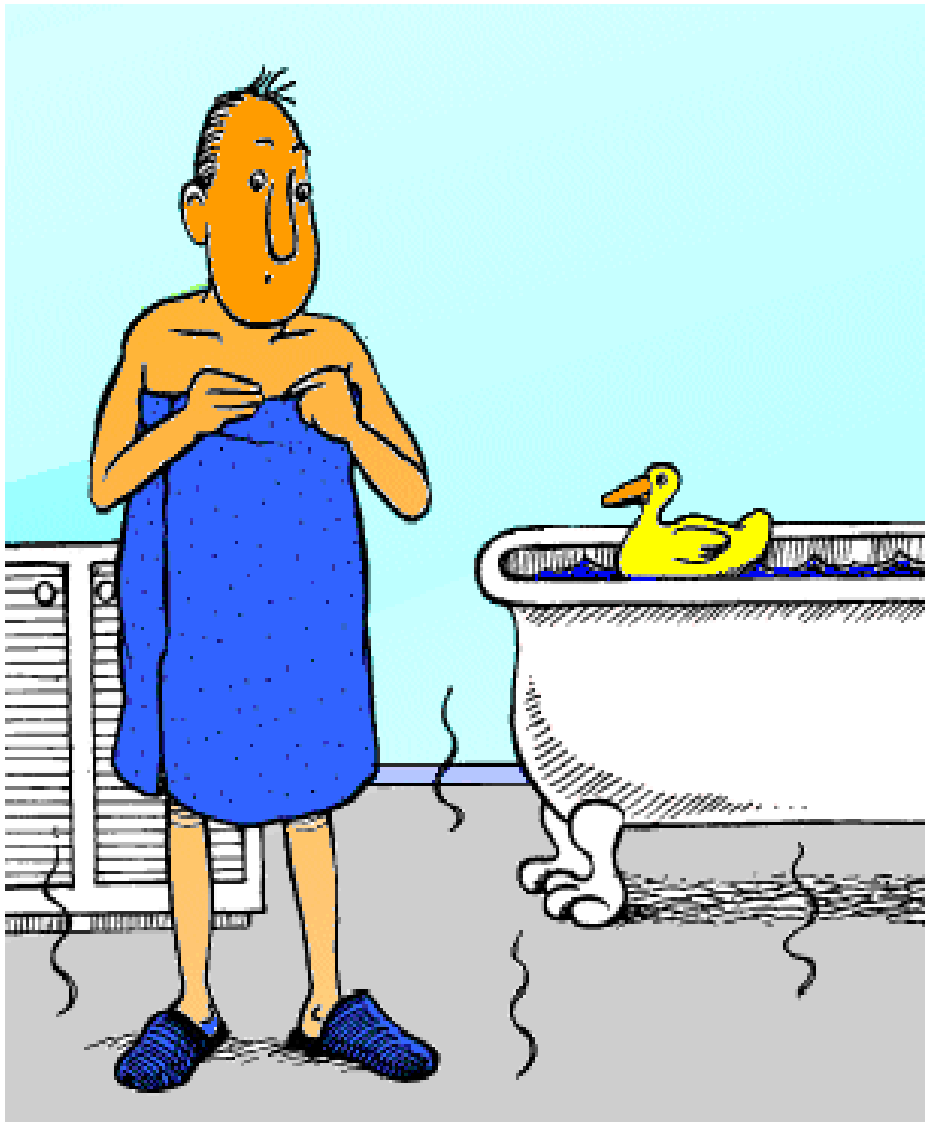
Vertical Air Temperature Difference

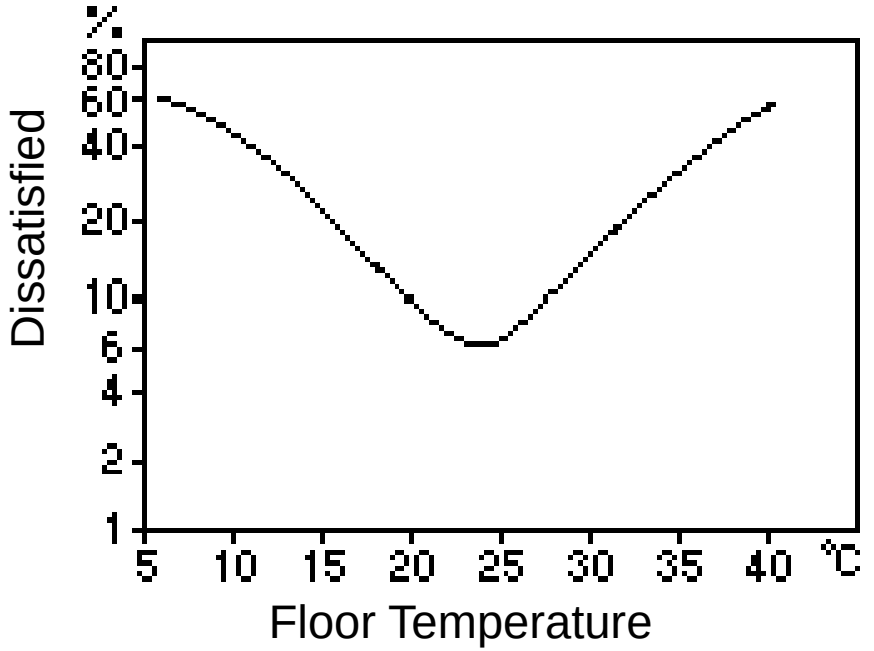




- Vertical Air Temperature Difference is the difference between Air Temperature at ankle and neck level

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

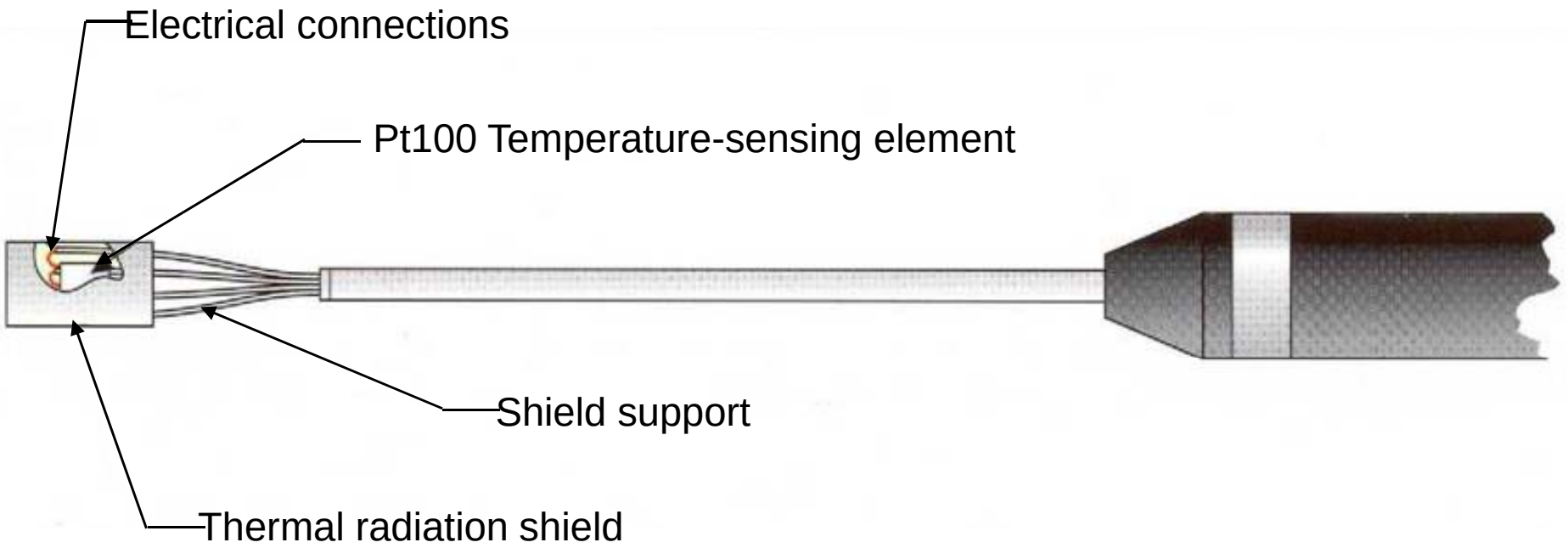
- Measurements of Vertical Temp. difference and Draught at ankle and neck
- Other measurements should be performed at persons centre of gravity

Collection of Thermal Comfort Data

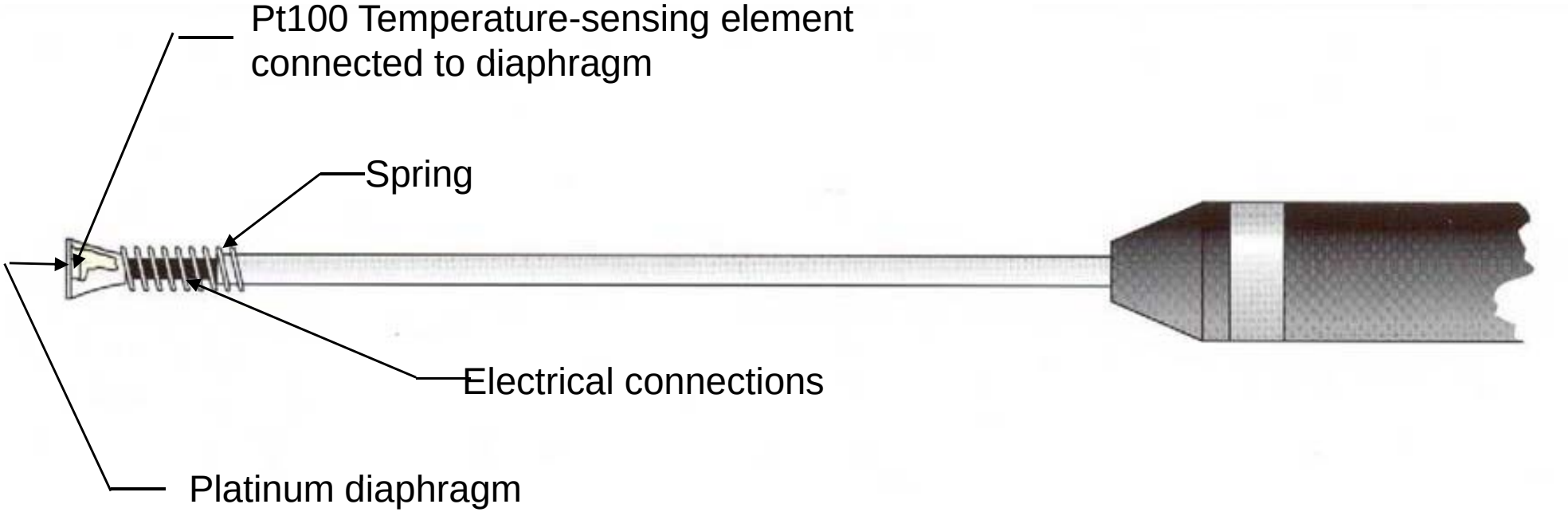
Transducers

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

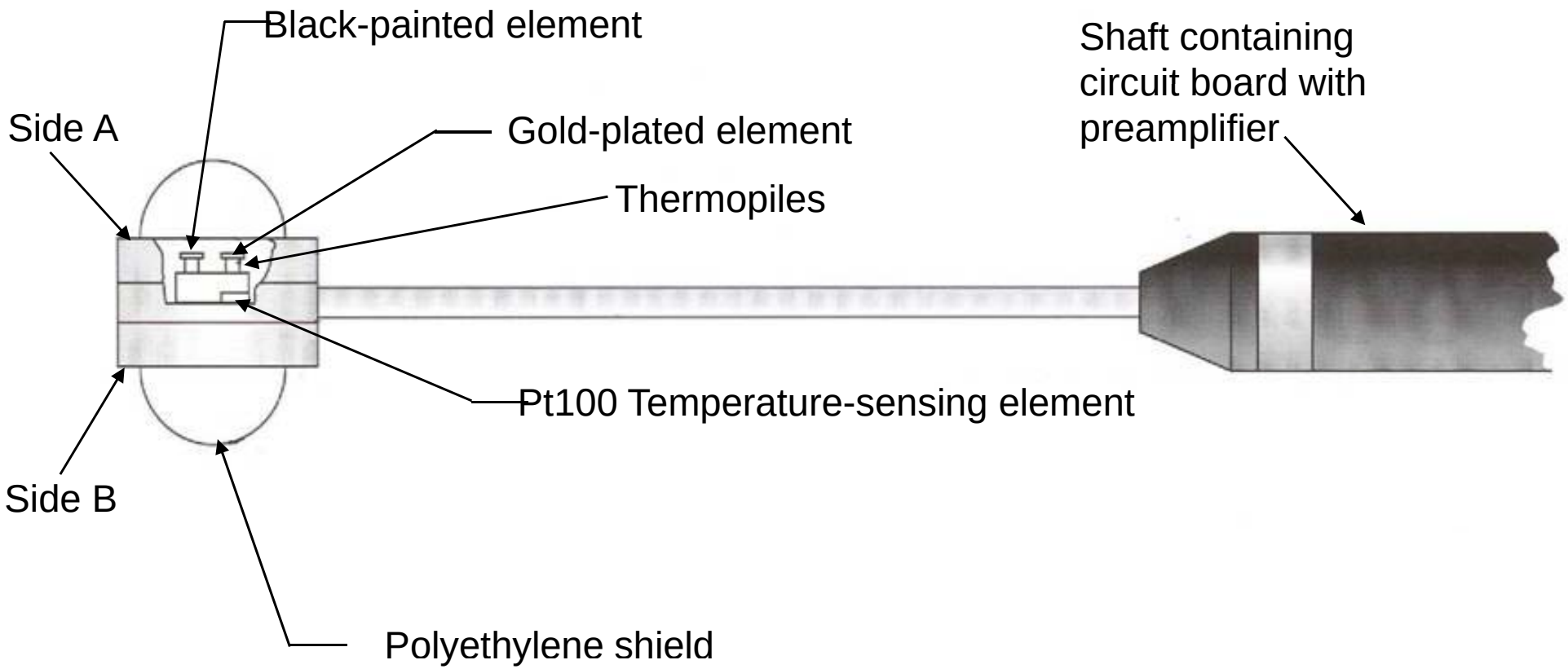
Air Temperature Transducer



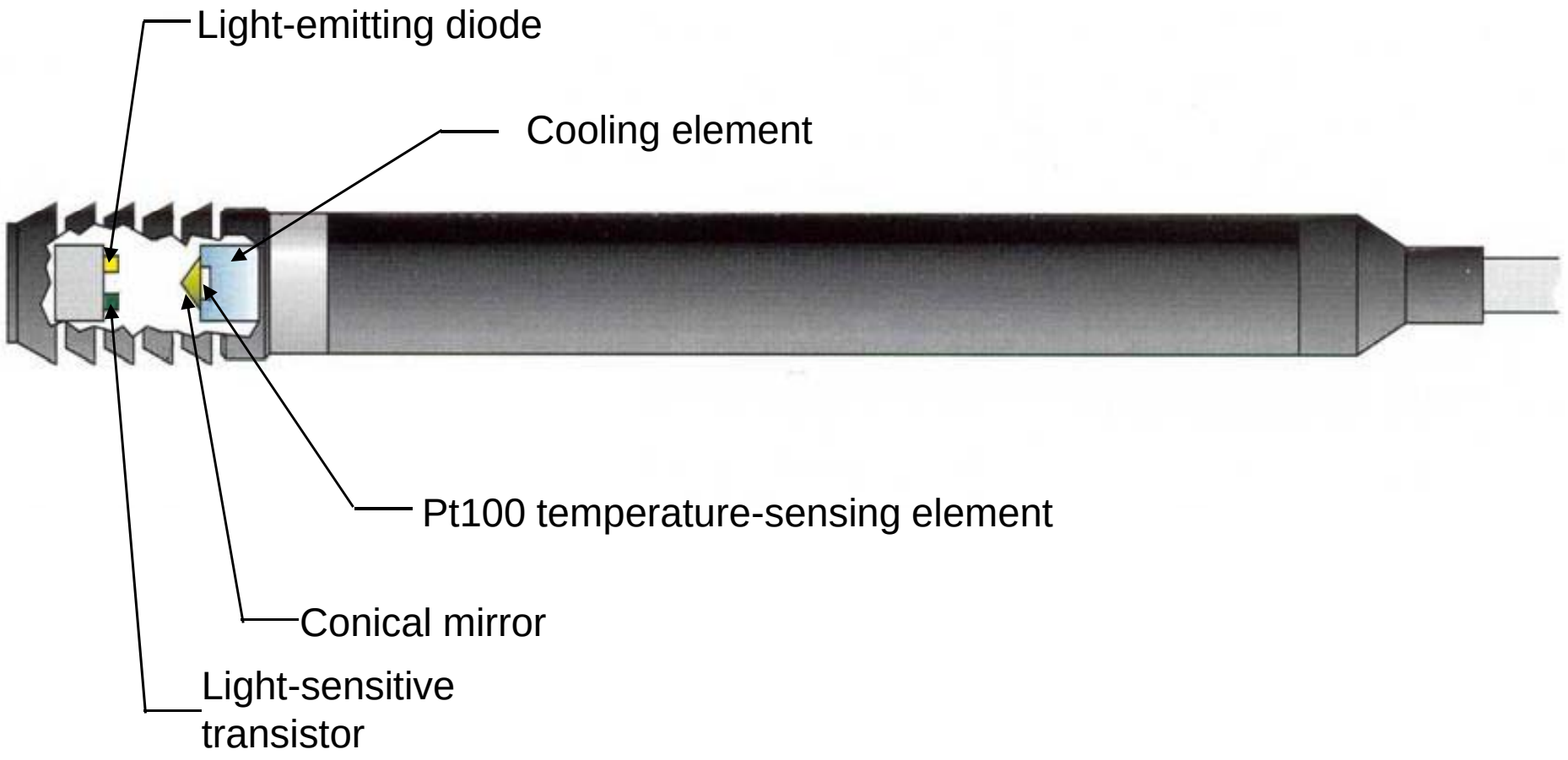
Surface Temperature Transducer



Radiant Temperature Asymmetry Transducer



Humidity Transducer

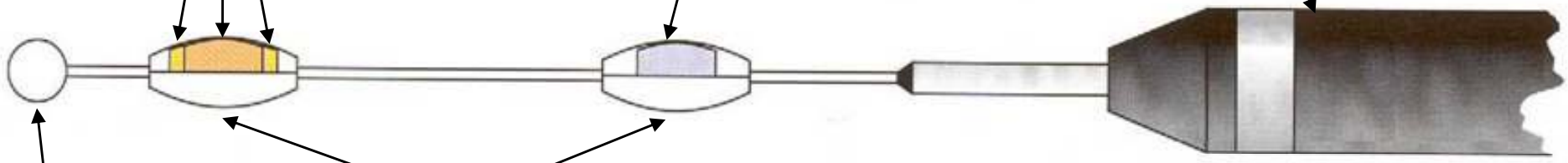


Air Velocity Transducer

Three heated coils. For improved frequency response, temperature and heat loss are only measured on the centre coil

Unheated coil of nickel wire

Shaft containing circuit board with measuring bridge



Plastic foam ellipsoid's coated with white enamel paint

Solid plastic sphere provides protection and correction for directional sensitivity

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.

Further Reading

- Butera, F. M., 1998. Principles of thermal comfort, *Renewable and Sustainable Energy Review*, 2 (1-2): 39-66. [online journal]
- Hui, C. M., 2005. Is 25.5 deg C comfortable?, article for "*ROTOR*" – the official publication of Engineering Society HKUSU, August (in Chinese)

E-learning & Web Links

- ASHRAE, 1997. *Thermal Comfort Tool* [computer program] [AV 697.9315 T41]
- Deringer Group, 1999. *EcoAdvisor: Energy Trainer for Energy Managers* [AV 697 E19]
- Thermal Comfort - CLEAR (Comfort and Low Energy ARchitecture) [London Metropolian University]
  - http://www.learn.londonmet.ac.uk/packages/clear/thermal/