POLITECNICO DI MILANO

Thermal Comfort

Ref : Thermal Comfort by Prof. Livio Mazzarella

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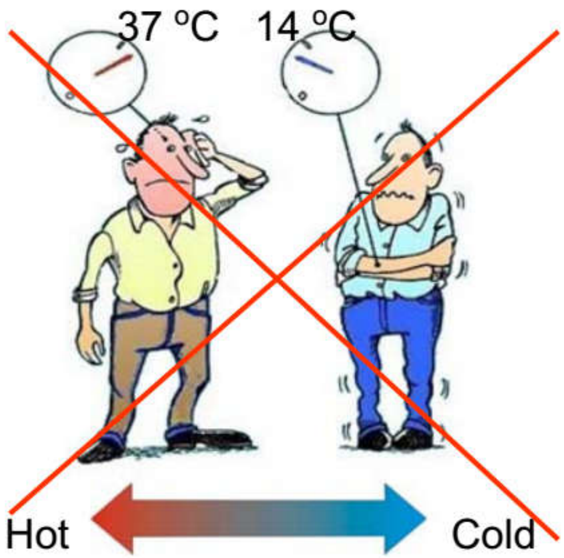
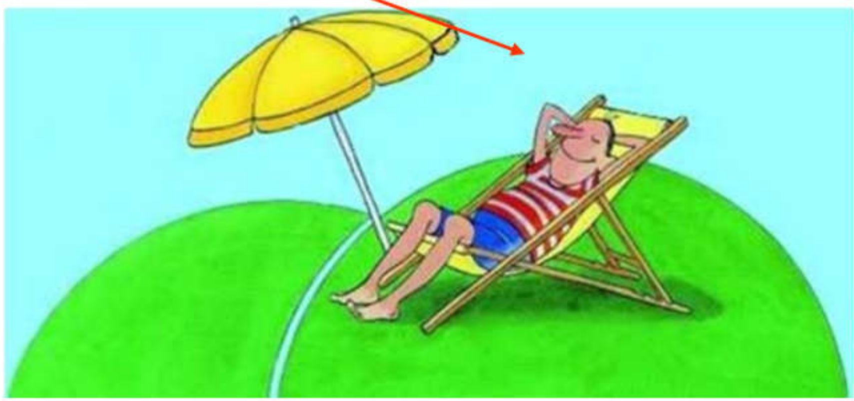
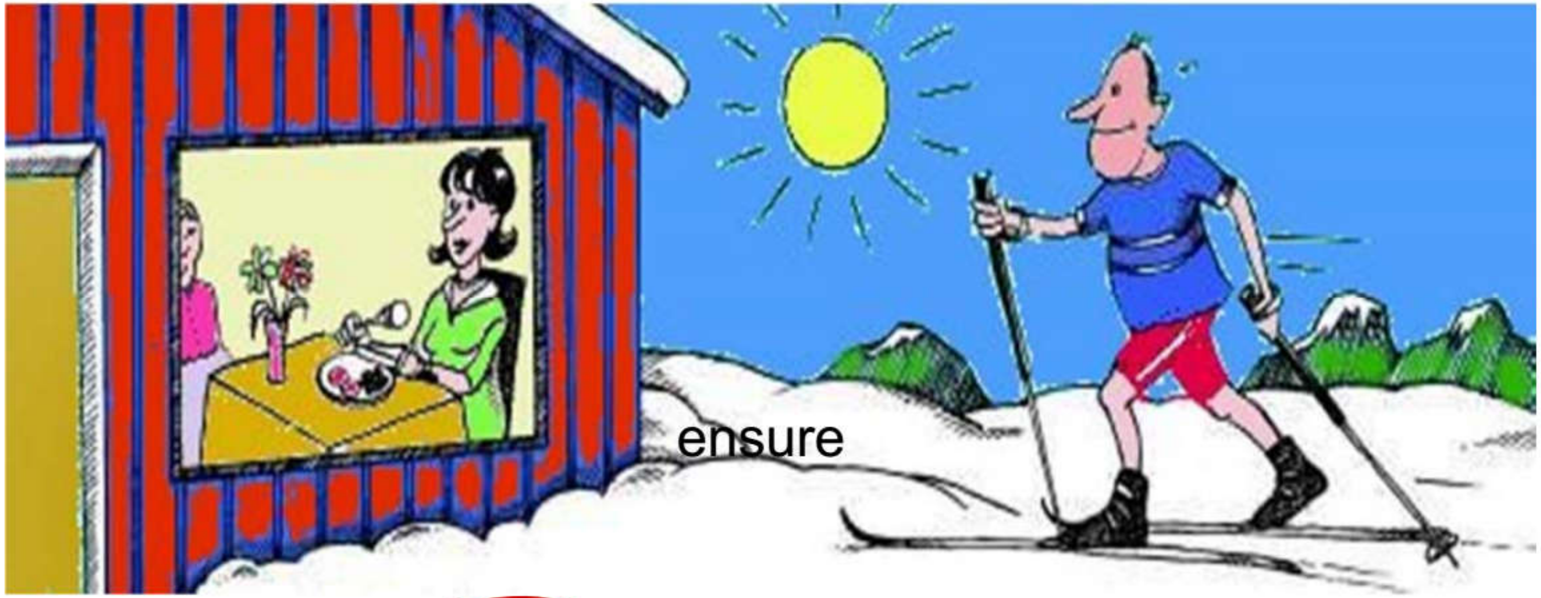
Building Design Tools able to ensure the Thermal Comfort with the Minimum Energy Cost





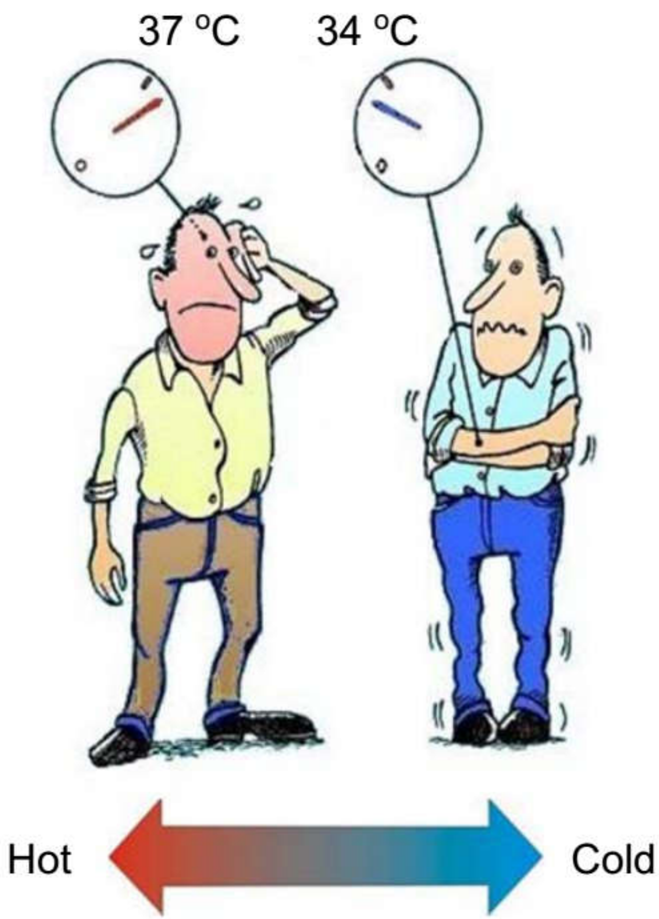


Definition

- That 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.

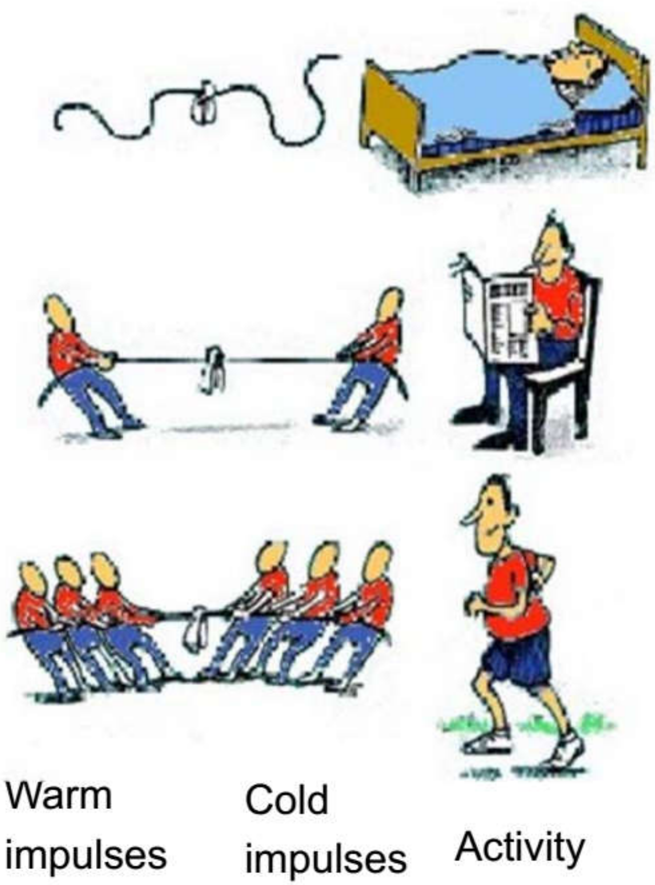
- Heat sensor is located in hypothalamus. Signals when temperature is higher than 37 °C.
- Cold sensors are located in the skin. Send signals when skin temperature is below 34 °C.

Heating mechanism:

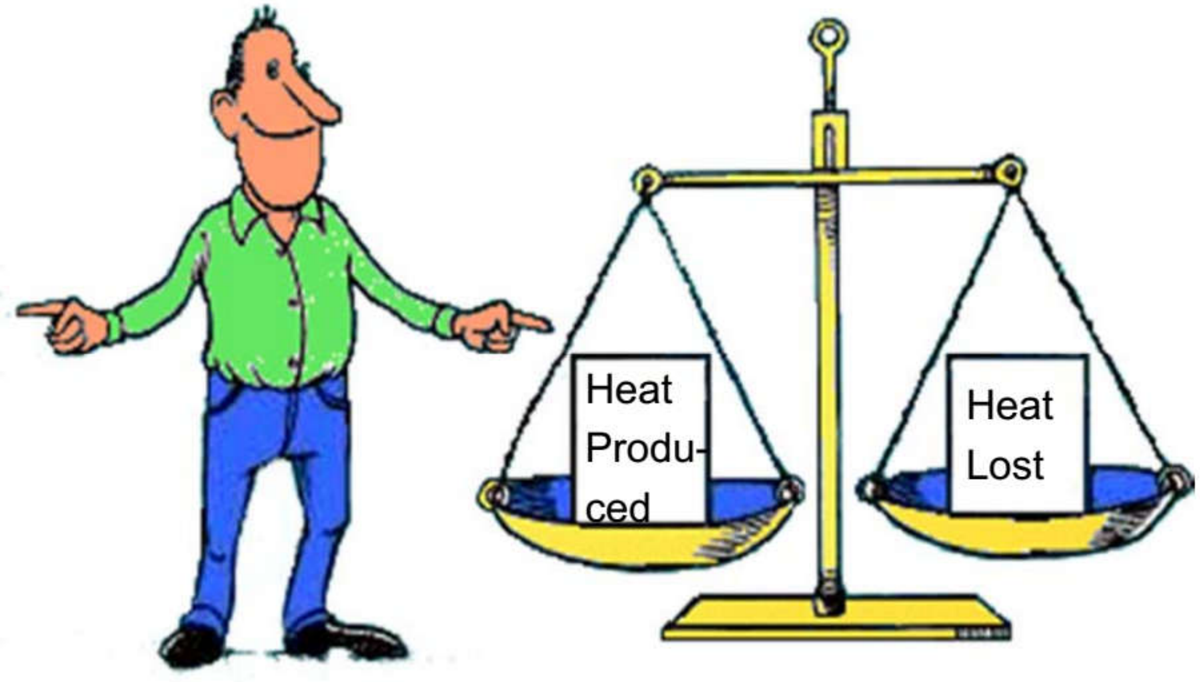
- Reduced blood flow (vasoconstriction)
- Shivering.

Cooling mechanism:

- Increased blood flow (vasodilation)
- Sweating (Evaporation).



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



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

$$\frac{dE_T}{dt} = \Phi_{E_C} - \dot{W} - \Phi_T$$

$$\frac{d(U + E_c)}{dt} = \Phi_{E_C} - \dot{W} - \Phi_T$$

$$\begin{cases} \dfrac{d(E_c)}{dt} = \Phi_{E_C} - \Phi_M \\ \dfrac{dU}{dt} = \Phi_M - \dot{W} - \Phi_T \end{cases}$$

The body energy change E_T by unit of time is due to

- net chemical advective flow (food), Φ_{Ec}
- mechanical power delivered by the body, $\dot{W}$
- net heat flux , Φ_T (positive if delivered form the body)

Dividing internal energy, U, from chemical energy, E_c, through the metabolic flow, Φ_M, the **heat balance equation** is obtained

Expressing internal energy as:

$$U = C \cdot T$$

the heat balance equation can be expressed in terms of temperature

$$C\frac{d\langle T\rangle}{dt} = \Phi_M - \dot{W} - \Phi_T$$

where C is the human body thermal capacity

$<T>$ is the average body temperature

If

$$\Phi_M - \dot{W} - \Phi_T > 0 \quad \Rightarrow \quad \langle T\rangle \uparrow \quad \text{grows}$$

$$\Phi_M - \dot{W} - \Phi_T < 0 \quad \Rightarrow \quad \langle T\rangle \downarrow \quad \text{decreses}$$

General heat balance

$$S = M - W - E - (R + C) \qquad [W/m^2]$$

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 (latent heat)

R + C = dry heat exchange through radiation & convection (sensible heat)

A_{cu} = skin area of human body

$$\frac{dU}{dt} = A_{cu} \cdot S \;\; ; \; \Phi_M = A_{cu} \cdot M \;\; ; \; \dot{W} = A_{cu} \cdot W \quad ; \quad \Phi_T = A_{cu} \cdot (E + R + C)$$

- Rate of heat storage, S ➡ $$\frac{dU}{dt} = cV\frac{d\langle T\rangle}{dt}$$
  - 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

The Heat Balance Equation

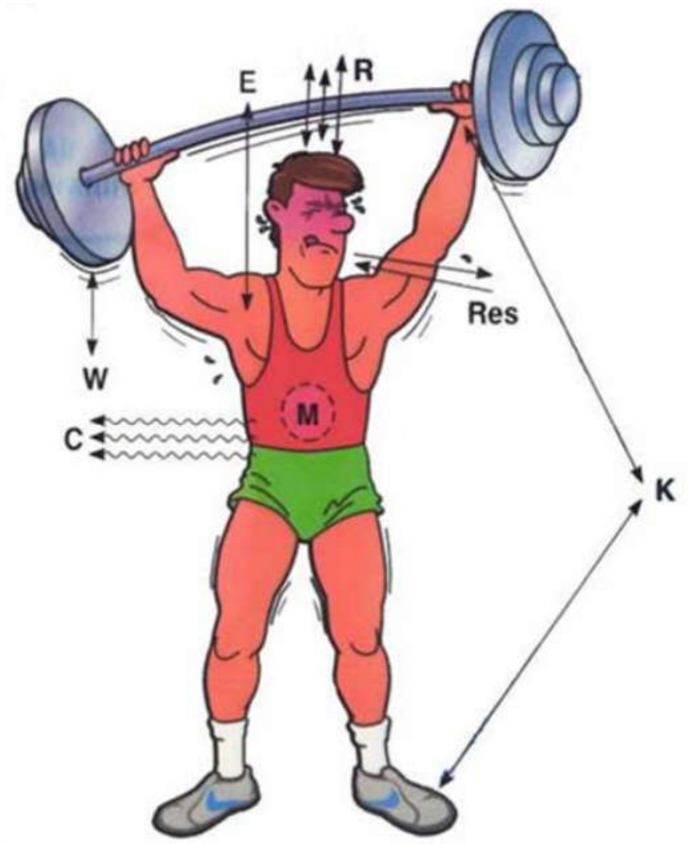
- Mechanical work, W
  - energy in human body transformed into external mechanical work
  - can be expressed as function of the metabolic rate M through the mechanical efficiency of the human body:

$$\eta = \frac{W}{M}$$

which is quite low, $0 < \eta < 0.2$

- 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})

The Energy Balance



Parameters influencing the Heat Loss from a person

- The **dry heat loss (R+C)** represents ~70% at low Clo-values and ~60% at higher Clo-values
- The **latent heat exchange** for perspiration / sweating (**E**) represents the ~ 25% for moderate activities
- Conductive (**K**) and breathing heat transfer (**Res**) are normally insignificant compared to the total heat exchange
- The mechanical interaction (W), due to a low mechanical efficiency (<20%), is only a few %.

The Comfort Equation

Standard EN ISO 7730

$$\frac{dU}{dt} = \Phi_M - \Phi_T - W \quad \rightarrow \quad C_{cu}\frac{d\langle T_{cu}\rangle}{dt} = A_{skin}\{M - H - E_c - C_{res} - E_{res} - W\} = A_{skin}\{M - W - \varphi_T\}$$

Hypotesis "*Comfort*" $\langle T_{cu}\rangle \cong 37\,°C = \text{constant} \quad \rightarrow \quad \{M - H - E_c - C_{res} - E_{res} - W\}_{comfort} = 0$

con

$$H = R + C = 5.67\cdot 10^{-8}\cdot\varepsilon_{cl}\cdot f_{cl}\cdot\left[(\vartheta_{cl}+273)^4\cdot-(\overline{\vartheta_r}+273)^4\right] + f_{cl}h_c(\vartheta_{cl}-\vartheta_a)$$

$$E_c = 3.05\cdot 10^{-3}\cdot\left[5733 - 6.99\left(M - W - p_v^{(H_20)}\right)\right] + 0.42\cdot(M - W - 58.15)$$

$$C_{res} = 0.0014\cdot M\cdot(34 - \vartheta_a) \qquad E_{res} = 1.72\cdot 10^{-5}\cdot M\cdot\left(5867 - p_v^{(H_2O)}\right)$$

$$\vartheta_{cl} \cong \vartheta_{cl,eq} = \vartheta_{sk,eq} - I_{cl}\cdot H = [35.7 - 0.028\cdot(M - W)] - I_{cl}\cdot H$$

M	metabolic rate	f_{cl}	clots factor
H	sensible heat transfer (R+C)	ε_{cl}	clots emissivity = 0.7
E_c	latent heat transfer from the skin	ϑ_{cl}	clots temperature [°C]
C_{res}	sensible breathing heat transfer	$\vartheta_{sk,eq}$	equilibrium skin temperature [°C]
E_{res}	latent breathing heat transfer	ϑ_a	air temperature [°C]
W	specific mechanical power	ϑ_r	mean radiant temperature [°C]
I_{cl}	clots thermal resistance	$p_v^{(H_2O)}$	water vapour partial pressure
h_c	convective heat transfer coeff.; $h_c = f(v)$	v	air velocity

The convective-radiative heat transfer can be written as:

$$H = R + C = f_{cl} \cdot \left\{ h_r (\vartheta_{cl} - \overline{\vartheta}_r) + h_c (\vartheta_{cl} - \vartheta_a) \right\} =$$
$$= f_{cl} \cdot h_{cr} (\vartheta_{cl} - \vartheta_{operativa})$$

defining $$\overline{\vartheta}_r = \sqrt[4]{\overline{T}_r} - 273.15$$

$$h_r = \frac{\varepsilon_{cl} \sigma \left(T_{cl}^4 - \overline{T}_r^{\,4} \right)}{\vartheta_{cl} - \overline{\vartheta}_r}$$

radiative heat transfer coefficient

$$h_{cr} = h_r + h_c$$

combined convective-radiative C-R coe

$$\vartheta_o = \left. \frac{h_r \cdot \overline{\vartheta}_r + h_c \cdot \vartheta_a}{h_r + h_c} \right|_{human\ body}^{ambient}$$

OPERATIVE temperature

(relation between ϑ_r e ϑ_a)

$$f(M, W, I_{\mathrm{cl}}, \vartheta_a, \overline{\vartheta_r}, v, p_v^{(H_2O)}) = 0$$

The comfort equation includes the three personal parameters (***M*, *W*, I_{cl}**) and four ambient parameters (**ϑ_a, ϑ_r, *v*, $p_v^{(H2O)}$**)

Set personal parameters, there are three degrees of freedom!

... that is, any combination of 3 environmental parameters on 4 satisfies the equation welfare;

$$f_1(\vartheta_a, \overline{\vartheta_r}, v, p_v^{(H_2O)}) = 0$$

that is:

$$f_2(\vartheta_a, \vartheta_o, v, p_v^{(H_2O)}) = 0 \qquad f_3(\vartheta_o, \overline{\vartheta_r}, v, p_v^{(H_2O)}) = 0$$

if operative temperature is used

The Comfort Equation

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)

- Fanger's comfort criteria

  developed by Prof. P. O. Fanger (Denmark)

- **Fanger's comfort equation**:

$$f(M, I_{cl}, v, \vartheta_r, \vartheta_{db}, p_s) = 0$$

where M = metabolic rate (met)

I_{cl} = cloth index (clo)

v = air velocity (m/s)

ϑ_r = mean radiant temp. (^oC)

ϑ_{db} = dry-bulb temp. (^oC)

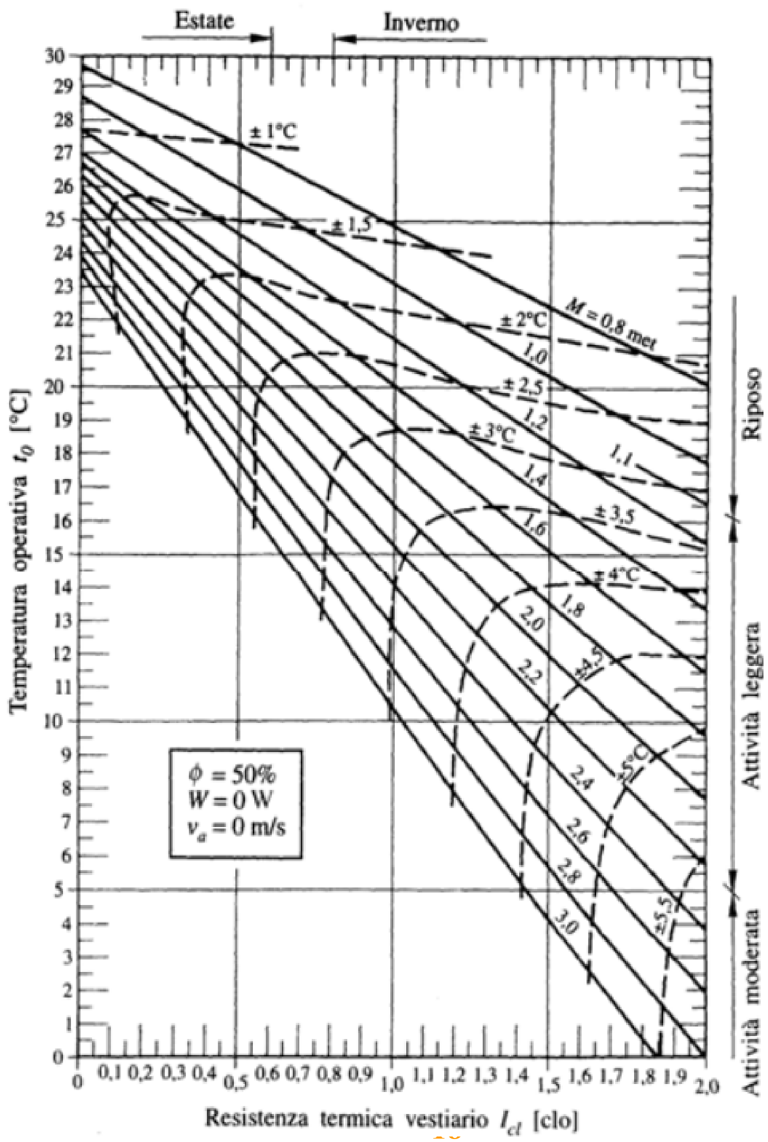
p_s = water vapour pressure (kPa)

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)

Solid lines: thermal neutrality (PMV=0) functions of ϑ_0 , I_{cl} and M.

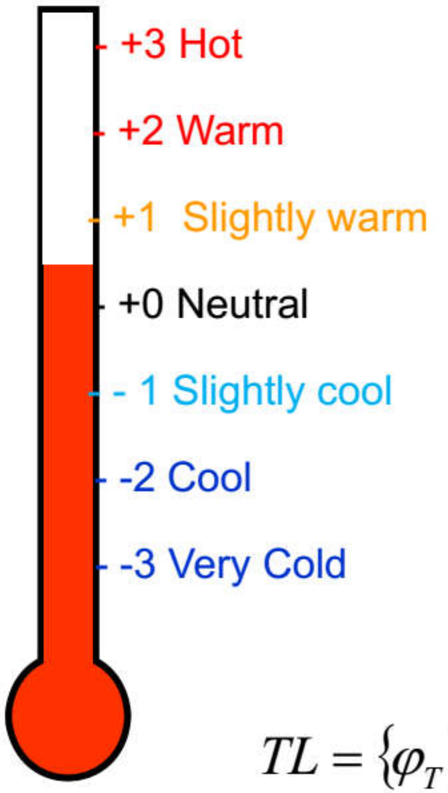
Dotted lines: acceptable deviation in °C of operative temperature ϑ_0 corresponding to (0.50<PMV<0.50)

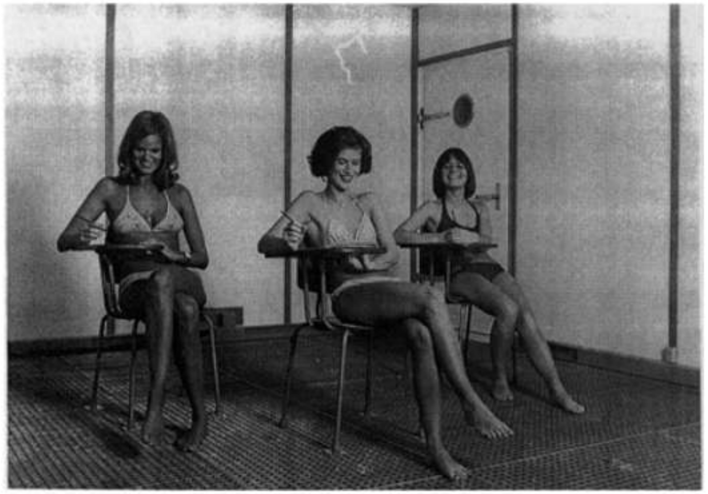


- **PMV**
  - a complex function of six major comfort parameters;
  - predict mean value of the subjective ratings of a group of people in a given environment
- **PPD**
  - determined from PMV as a quantitative measure of thermal comfort
  - ‘dissatisfied’ means not voting -1, +1 or 0 in PMV
  - normally,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

The Predicted mean vote scale

The PMV index is used to quantify the degree of discomfort



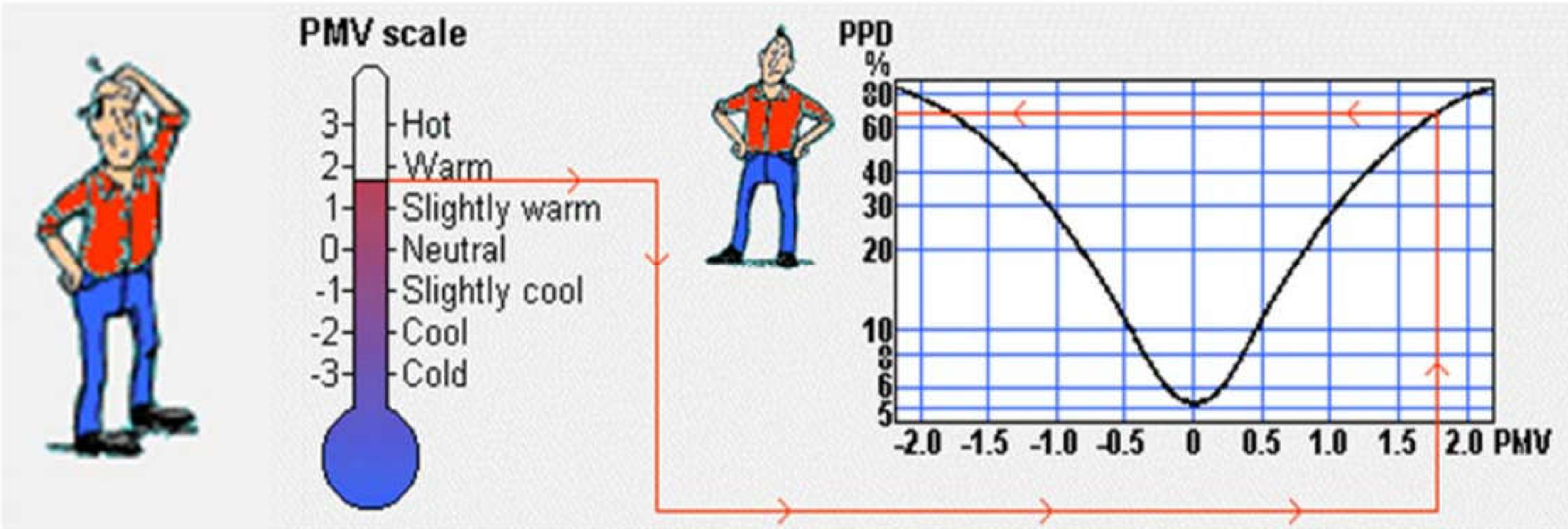


$$PMV = (0.303e^{-0.036M} + 0.028) \cdot TL$$

$$PPD = 100 - 95e^{-(0.03353 PMV^4 + 0.2719 PMV^2)}$$

$$\varphi_T = H + E_c + C_{res} + E_{res}$$

$$TL = \{\varphi_T\}_{comfort} - \{\varphi_T\}_{actual\ conditions} = (M - W) - \{\varphi_T\}_{actual\ conditions}$$



- PMV-index (Predicted Mean Vote) predicts the subjective ratings of the environment in a group of people.
- PPD-index predicts the number of dissatisfied people.

From the comfort equation and the relationship *PMV-TL,*

when:

- ***R.H.*** $\cong$ 50% ($\propto$ $p_v^{(H2O)}$)
- v_{air} < 0.15 m/s

there is thermal comfort if:

$$\vartheta_o = \left. \frac{h_r \cdot \overline{\vartheta}_r + h_c \cdot \vartheta_a}{h_r + h_c} \right|_{corpo\ umano}^{ambiente} \cong 20\,°C$$

winter clots

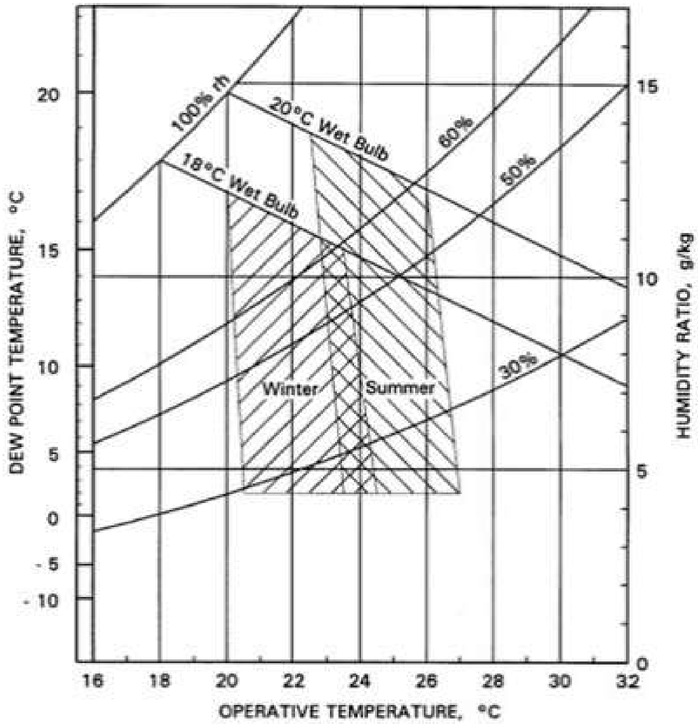
$$\vartheta_o \cong 25\,°C$$

summer clots

OPERATIVE temperature has to be controlled

ASHRAE Comfort zones (ASHRAE Standard 55)

- defined using isotherms parallel to ET (different comfort index)
- 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 °C ≤ SET ≤ 26.1 °C
  - for winter, 20.0 °C ≤ SET ≤ 23.9 °C



NB: ET = Effective Temperature

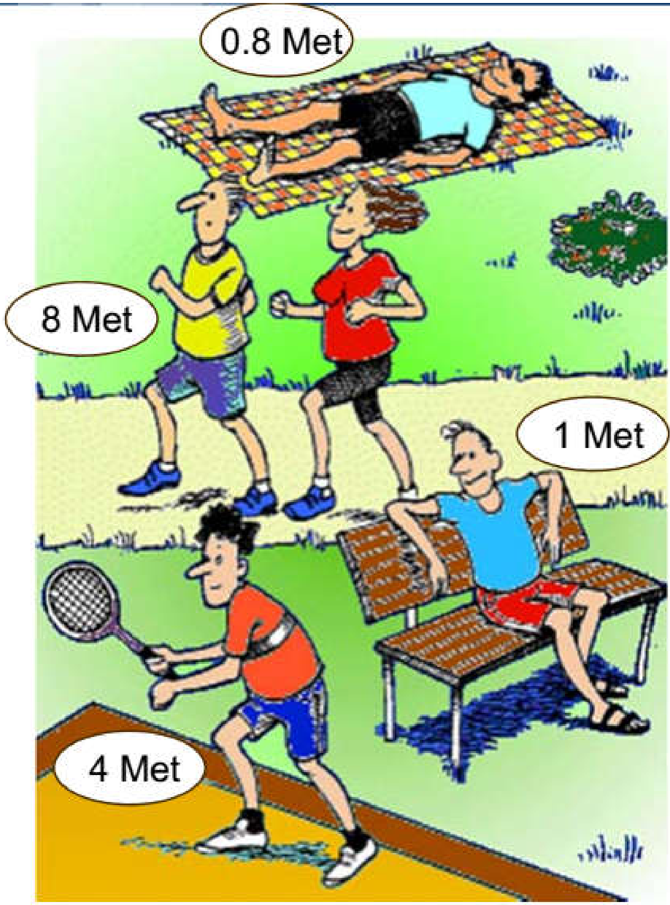
SET = Standard Effective Temp.

Parameters to be estimated

Parameters to estimate and calculate are:

Met	Estimation of Metabolic rate
Clo	Calculation of Clo-value

Metabolic Rate

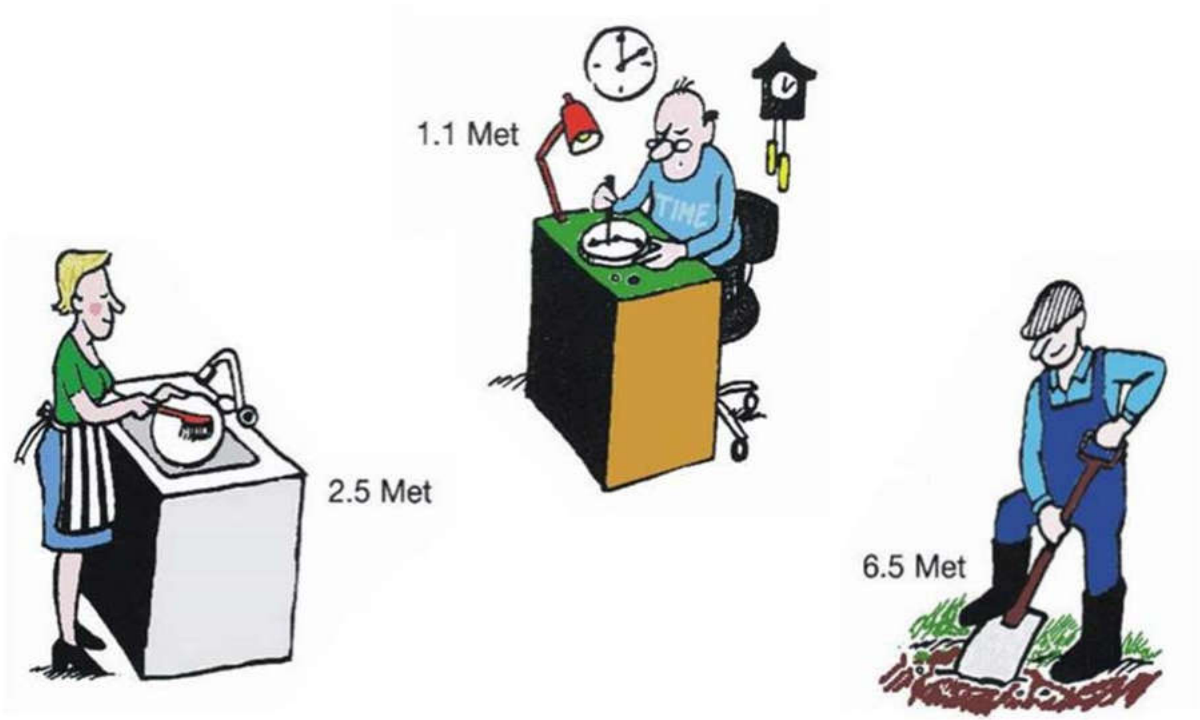


- Energy released by metabolism depends on muscular activity.
- Metabolism is measured in Met (1 Met=58.15 W/m^2 body surface).
- Body surface for normal adult is 1.7 m^2.
- A sitting person in thermal comfort will have a heat loss of 100 W.
- Average activity level for the last hour should be used when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

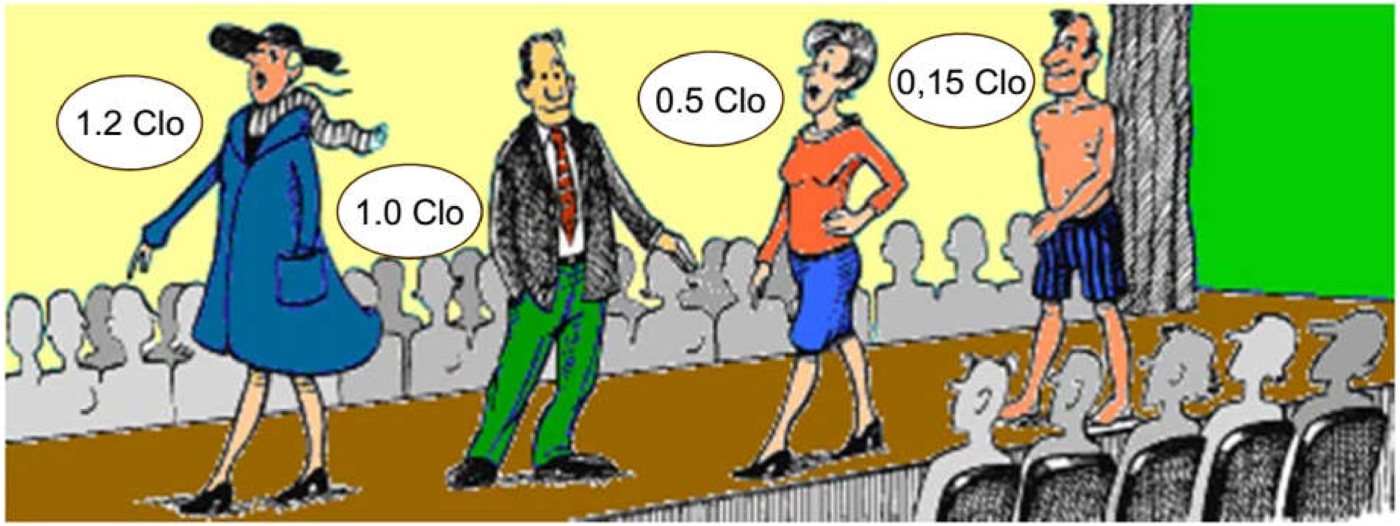
Metabolic Rate

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

Metabolic Rate



Insulation of clothing



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

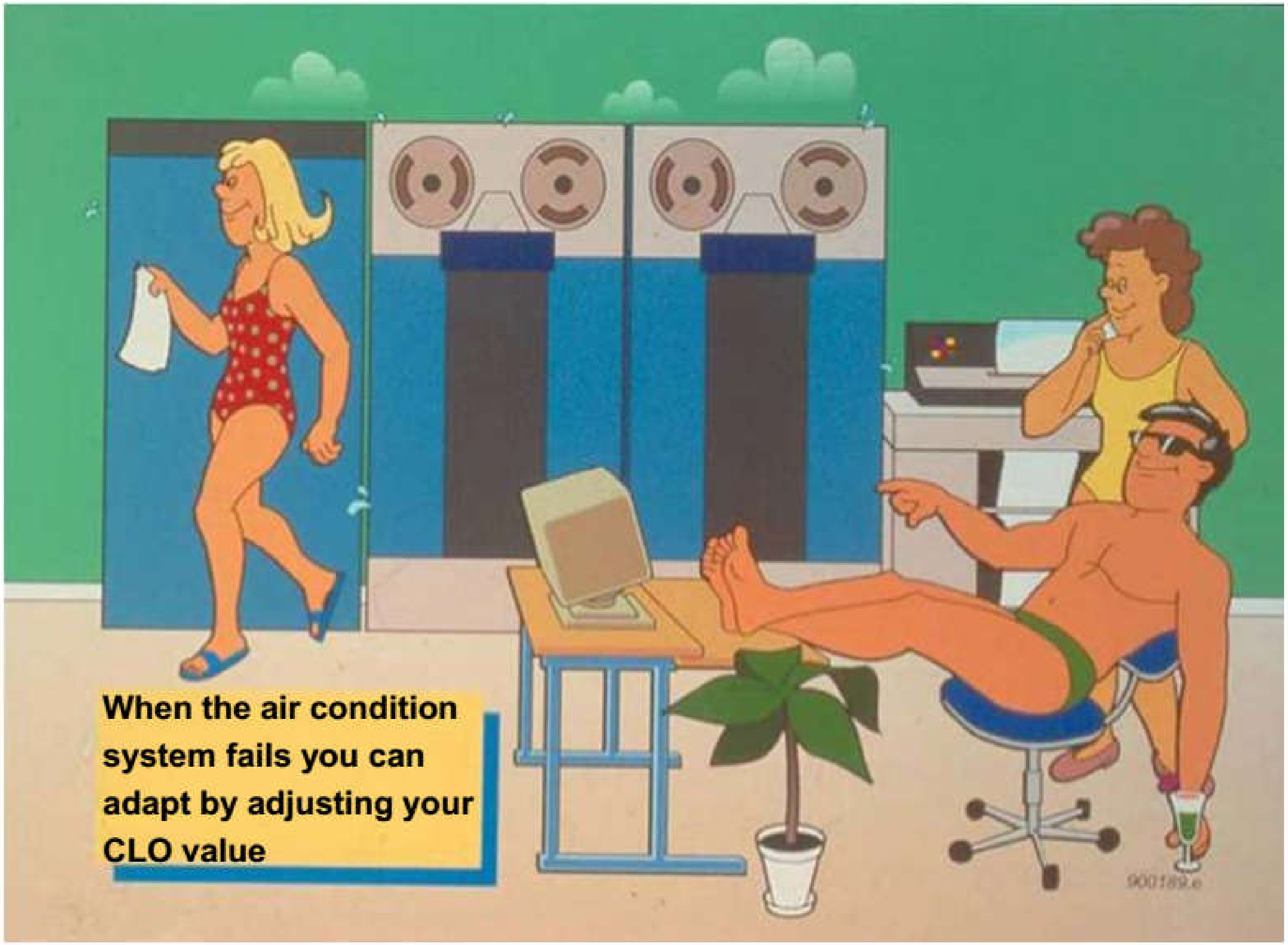
Insulation of clothing

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

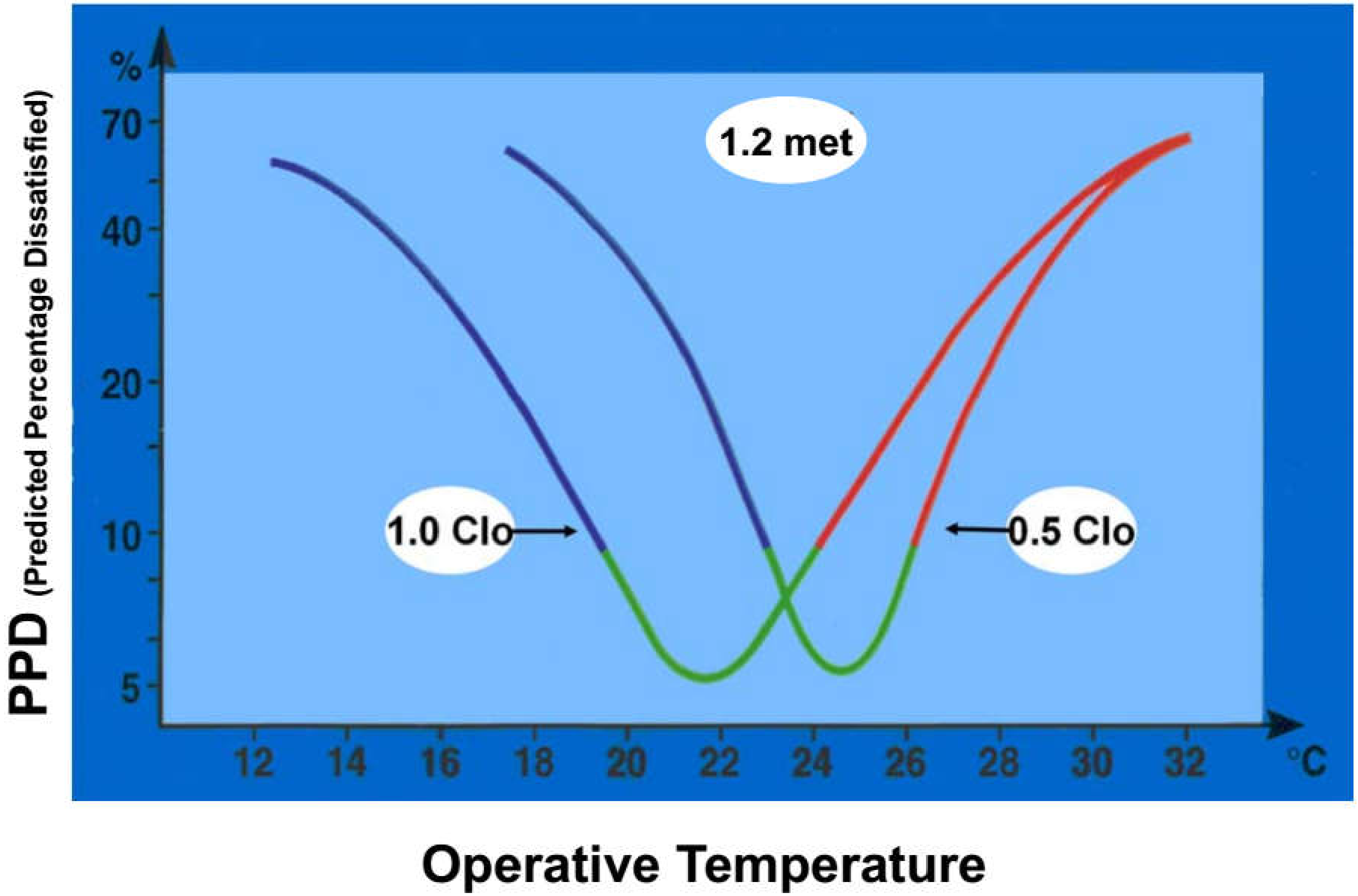
Insulation of clothing

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

Adaptation !


When the air condition
system fails you can
adapt by adjusting your
CLO value

Adjustment of Clothing!



Parameters to be measured!

Parameters to measure are:

- ϑ_a Air Temperature
- ϑ_r Mean Radiant Temperature
- v_a Air Velocity
- p_v Humidity (water vapour partial pressure)

Draught

Radiation Asymmetry

Vertical Air Temperature Differences.

Floor temperature

- In the project of Climate Sensitive Building, where the *climate control is basically natural*, except possibly for limited periods of the year, an important aspect concerns the definition of the comfort objectives the project has to focus on.
- These objectives can not be those used for air-conditioned buildings by the EN ISO 7730 standard and ASHRAE 55 Standard.
- These standards, widely used internationally, define the comfort objectives regardless of the context of climate and type of buildings.
- They were developed as reference tools for the design of air-conditioned buildings throughout the course of the year.

In such buildings the expectation of the subjects is that of a hygrothermal environment defined in terms almost static, without any possibility of adjustment.
A small change compared to the standard conditions of humidity is resentful negatively

This type of *expectation* depends on a kind of psychological cultural conditioning that leads to accept non-natural situations, induced by living in artificial environments.

In the approach of the ASHRAE adaptive comfort, the optimum comfort temperature of the indoor environment (expressed in terms of operative temperature) was showed to be dependendent on the external temperature.

To show such correlation, the mean outdoor effective temperature (ET*) has been taken as the outdoor temperature index.

The ET * is defined as the dry bulb temperature (ϑ_{DB}) with constant relative humidity of 50%, which allows an exchange radiative, convective and evaporative similar environment in analysis.

On the base of such research the ASRAE standard 55 was updated including a Adaptive Comfort Model for naturally ventilated building.

The outdoor climatic environment for each building was characterized in terms of mean outdoor dry bulb temperature $T_{a,out}$, instead of ET*. Optimum comfort temperature, T_{comf}, was then similar to the regression shown in the right side of Fig. 2, but re-calculated based on mean $T_{a,out}$, obtaining:

$$T_{comf} = 0.31 \cdot T_{a,out} + 17.8 \qquad (°C)$$