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Thermal Comfort

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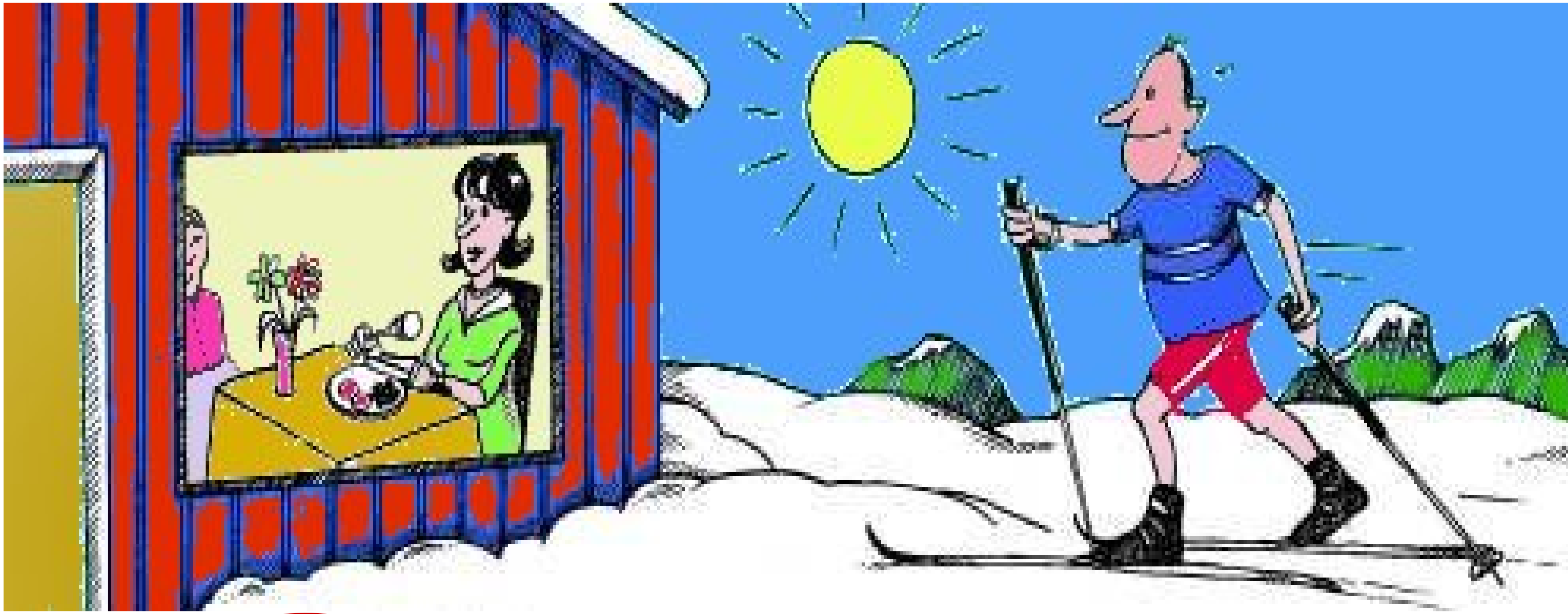
Acknowledgement:
Cartoons and certain figures are taken from: http://www.innova.dk/

What is Thermal Comfort?



Definition

That condition of mind which expresses satisfaction with the thermal environment. **ISO 7730: 1995**

That condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation.
ANSI/ASHRAE Standard 55-2004

BRITISH STANDARD

BS EN ISO 7730:1995

Incorporating Amendment No. 1

Moderate thermal environments — Determination of the PMV and PPD indices and specification of the conditions for thermal comfort

The European Standard EN ISO 7730:1995 has the status of a British Standard

BSI

ANSI/ASHRAE Standard 55-2004
(Supersedes ANSI/ASHRAE Standard 55-1992)

ASHRAE STANDARD

Thermal Environmental Conditions for Human Occupancy

Approved by the ASHRAE Standards Committee on January 24, 2004; by the ASHRAE Board of Directors on January 29, 2004; and by the American National Standards Institute on April 16, 2004.

ASHRAE Standards are scheduled to be updated on a five-year cycle; the date following the standard number is the year of ASHRAE Board of Directors approval. The latest copies may be purchased from ASHRAE Customer Service, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: *orders@ashrae.org*. Fax: 404-321-5478. Telephone: 404-636-8400 (worldwide) or toll free 1-800-527-4723 (for orders in U.S. and Canada).

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When addenda or interpretations to this standard have been approved, they can be downloaded free of charge from the ASHRAE web site at http://www.ashrae.org/template/TechnologyLinkLanding/category/1631 or http://www.ashrae.org/template/TechnologyLinkLanding/category/1686.

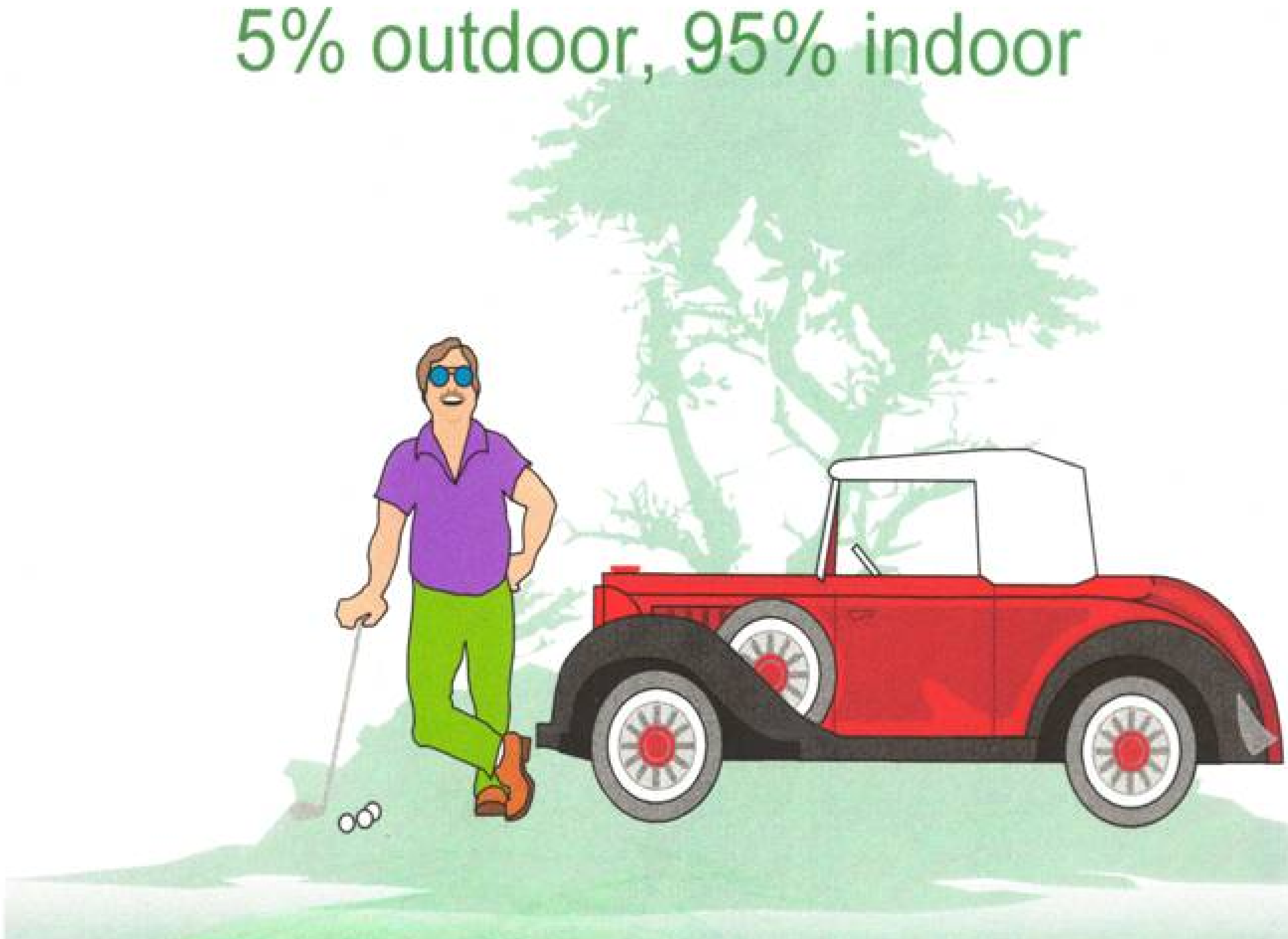
Approved American National Standard

ANSI

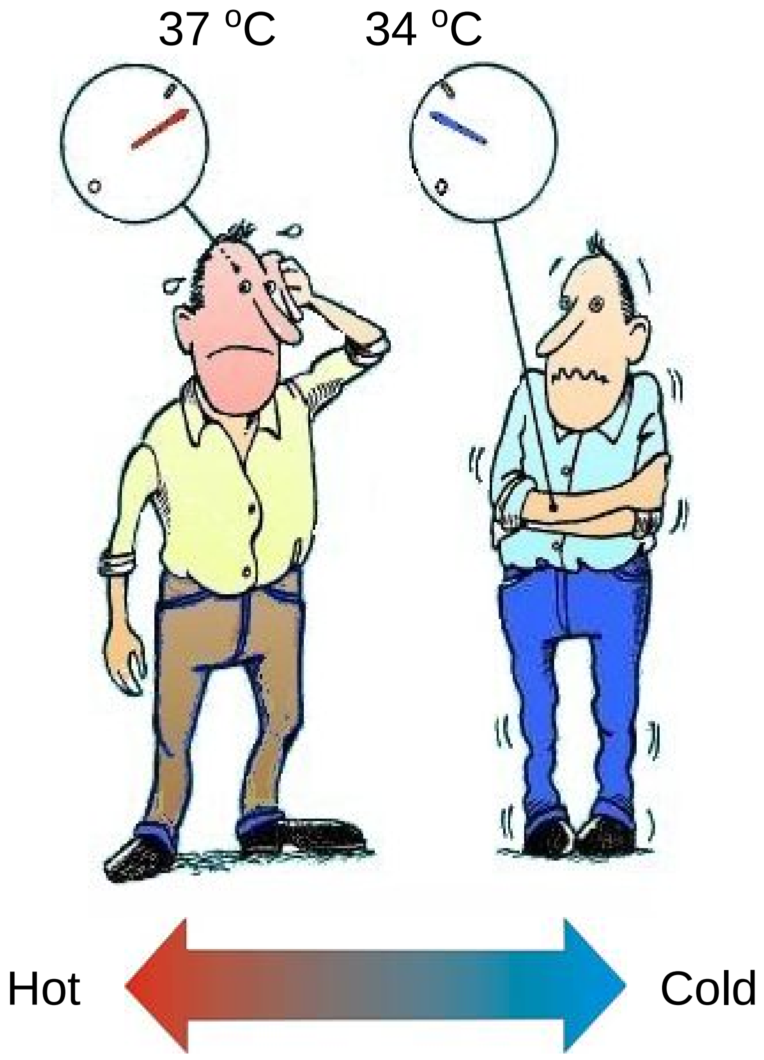
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
1791 Tullie Circle, NE • Atlanta, GA 30329

Thermal Environments

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

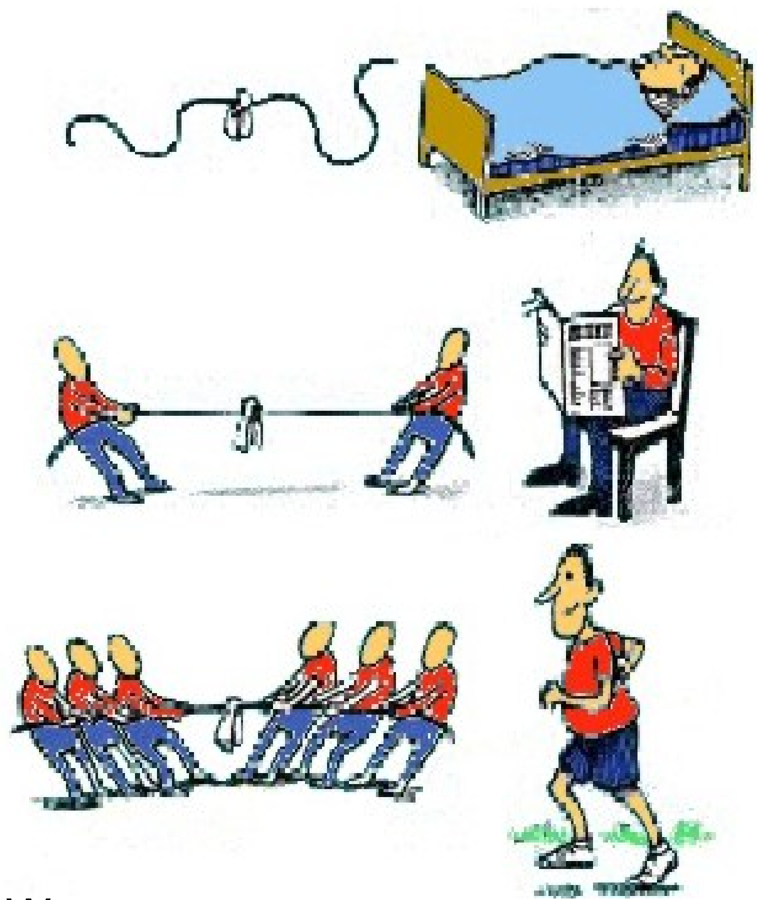


Body Temperature



- Normal body core temperature: 37°C.
- We have separate Heat- and Cold-sensors.
  - Heat sensor is located in hypothalamus （丘腦下部）. Sends out 'hot' signals when temperature is higher than 37°C.
  - Warming mechanism
    - Reduced blood flow over skin.
    - Shivering to increase muscle activity (increase metabolism).
  - Cold sensors are located on the skin. Sends out 'cold' signals when skin temperature is below 34°C.
  - Cooling mechanism
    - Increased blood flow over skin to increase heat loss.
    - Sweating (Evaporation).

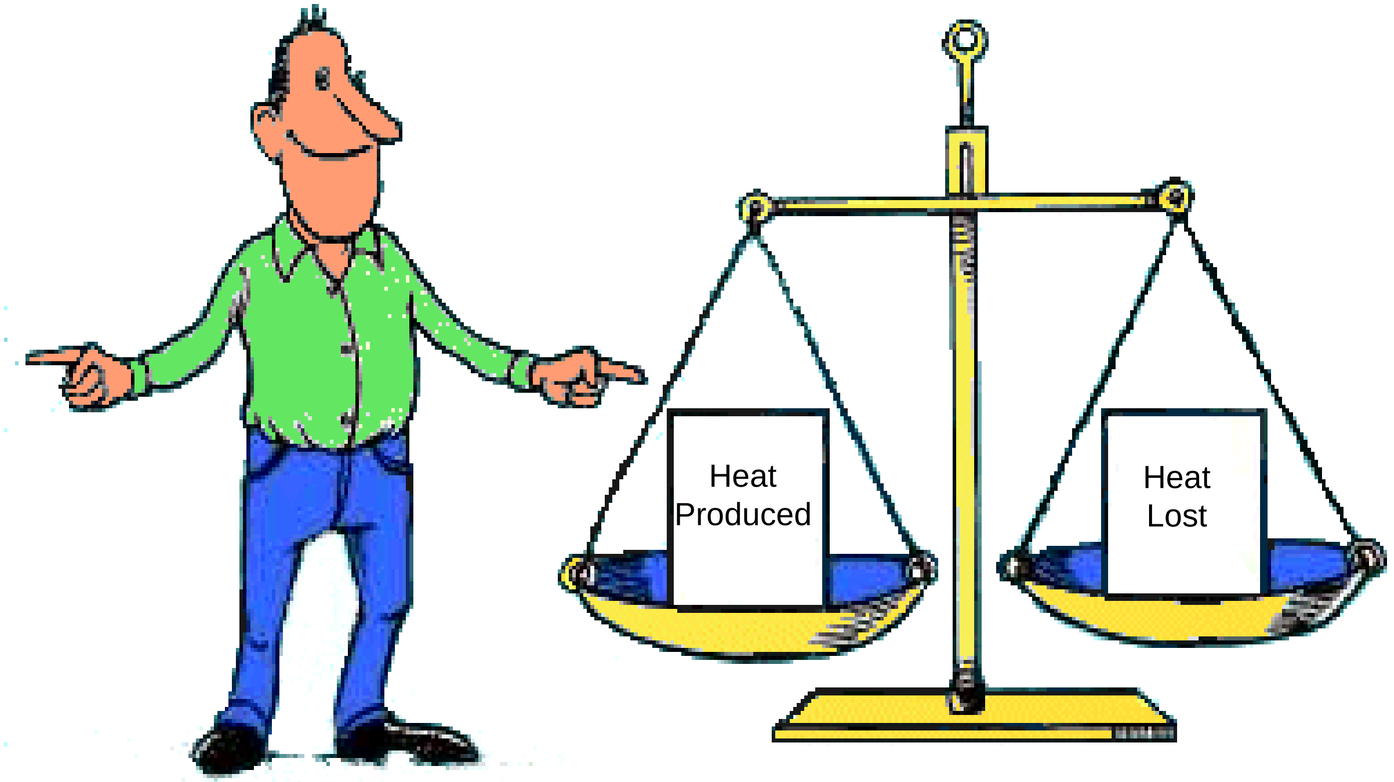
Perception of Thermal Environment



Warm impulses | Cold impulses | Activity

- 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.

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

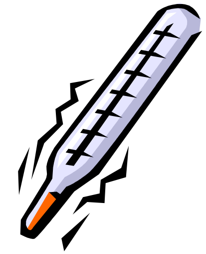
R + C = dry heat exchange through radiation & convection

Heat Balance Equation

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

- Rate of heat storage, S
  - proportional to rate of change in mean body temp.
  - normally, S =0
    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

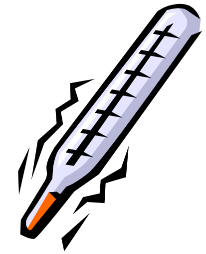
Heat Balance Equation



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

- 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})

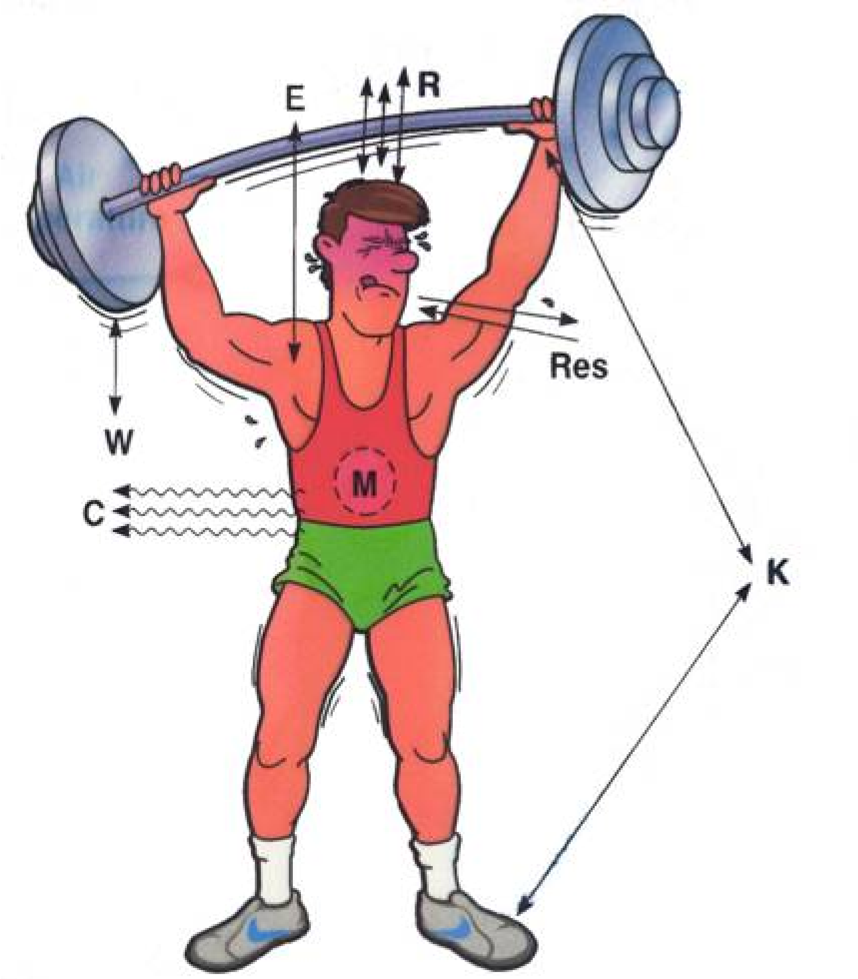
Heat Balance Equation



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

- 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

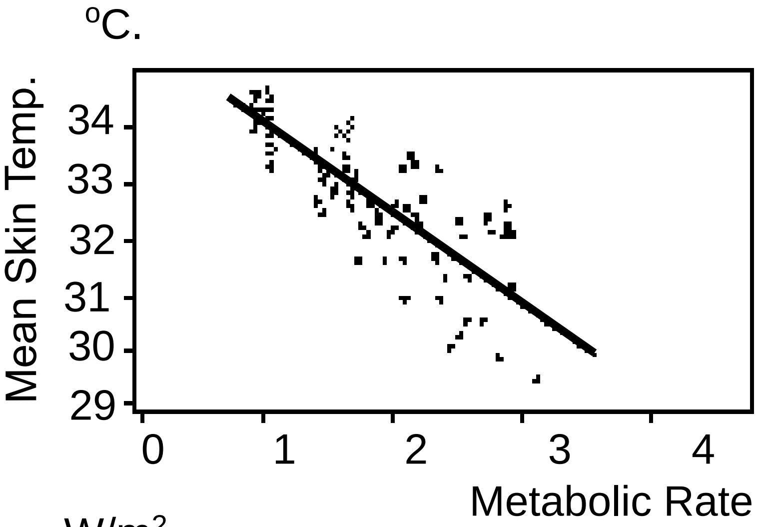
The Energy Balance

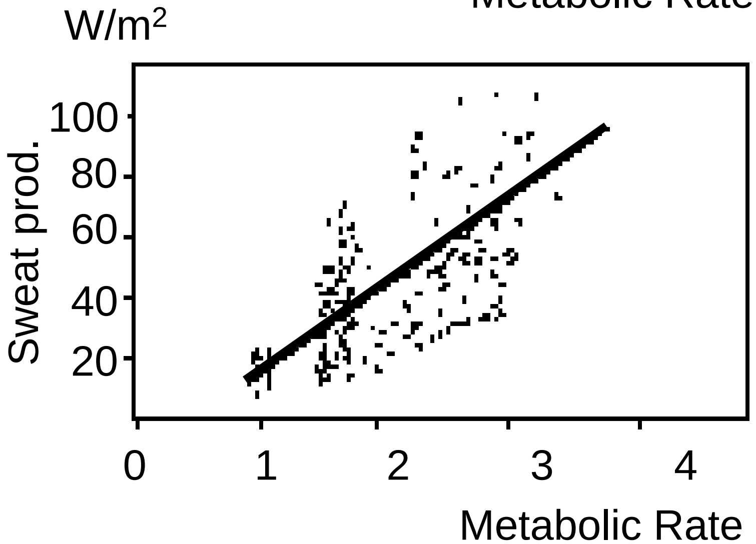


- The dry heat loss (R+C) constitutes ~70% at low Clo-values and ~60% at higher Clo-values
- Conduction (K) is normally insignificant compared to the total heat exchange

- 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.

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. (^oC)

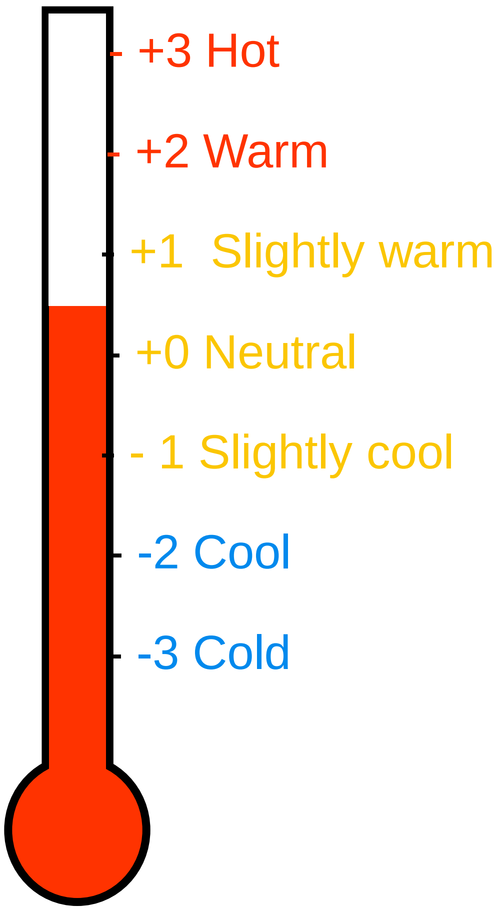
t_{db} = dry-bulb temp. (^oC)

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)

Predicted Mean Vote scale



The PMV index is used to quantify the degree of discomfort

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%

Calculation of PMV index

$$\text{PMV} \quad (0{,}303\, e^{-0{,}036M} + 0{,}028)\{(M - W) - 3{,}05 \times 10^{-3} \times [5\,733 - 6{,}99(M - W) - p_a] - 0{,}4 \times [(M - W) - 58{,}15] - 1{,}7 \times 10^{-5} M(5\,867 - p_a) - 0{,}001\,4M(34 - t_a) - 3{,}96 \times 10^{-8} f_{cl} \times \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right] - f_{cl} h_c (t_{cl} - t_a)\} \qquad \ldots(1)$$

where

$$t_{cl} = 35{,}7 - 0{,}028(M - W) - I_{cl}\Big\{3{,}96 \times 10^{-8} f_{cl} \times \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right] + f_{cl} h_c (t_{cl} - t_a)\Big\}$$

$$h_c = \begin{cases} 2{,}38(t_{cl} - t_a)^{0{,}25} & \text{for } 2{,}38(t_{cl} - t_a)^{0{,}25} > 12{,}1\sqrt{v_{ar}} \\ 12{,}1\sqrt{v_{ar}} & \text{for } 2{,}38(t_{cl} - t_a)^{0{,}25} < 12{,}1\sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1{,}00 + 1{,}290 I_{cl} & \text{for } I_{cl} \leqslant 0{,}078\ \text{m}^2\cdot{}^\circ\text{C/W} \\ 1{,}05 + 0{,}645 I_{cl} & \text{for } I_{cl} > 0{,}078\ \text{m}^2\cdot{}^\circ\text{C/W} \end{cases}$$

where

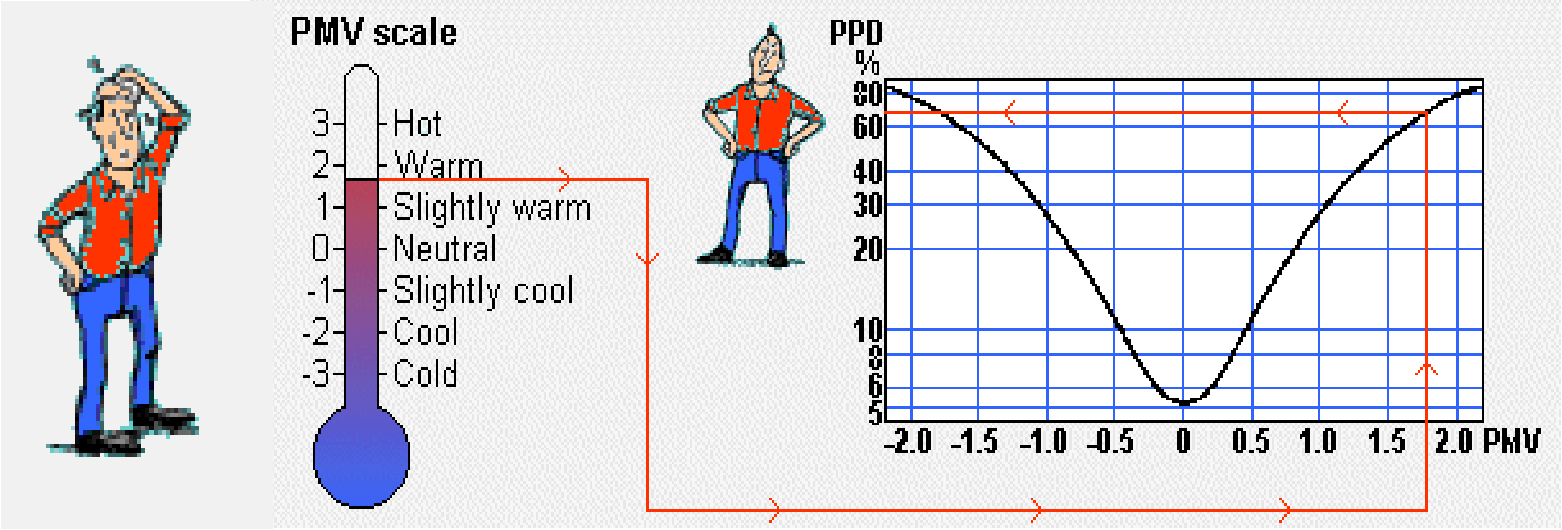
- PMV is the predicted mean vote;
- M is the metabolic rate, in watts per square metre of body surface area[a];
- W is the external work, in watts per square metre, equal to zero for most activities;
- I_{cl} is the thermal resistance of clothing, in square metres degree Celsius per watt[b];
- f_{cl} is the ratio of man's surface area while clothed, to man's surface area while nude;
- t_a is the air temperature, in degrees Celsius;
- $\bar{t}_r$ is the mean radiant temperature, in degrees Celsius;
- v_{ar} is the relative air velocity (relative to the human body), in metres per second;
- p_a is the partial water vapour pressure, in pascals;
- h_c is the convective heat transfer coefficient, in watts per square metre degree Celsius;
- t_{cl} is the surface temperature of clothing, in degrees Celsius.

[a] 1 metabolic unit = 1 met = 58,2 W/m^2
[b] 1 clothing unit = 1 clo = 0,155 m^2 ·°C/W

M = 46 W/m^2 to 232 W/m^2 (0,8 met to 4 met)
I_{cl} = 0 m^2 °C/W to 0,310 m^2 °C/W (0 clo to 2 clo)
t_a = 10 °C to 30 °C
$\bar{t}_r$ = 10 °C to 40 °C
v_{ar} = 0 m/s to 1 m/s

Reference: ISO 7730:1995

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.

$$PPD = 100 - 95 \times e^{-(0{,}033\,53 \times PMV^4 + 0{,}217\,9 \times PMV^2)}$$

C.2 Activity level = 58 W/m² (1 met)

ISO 7730:1995
PMV at 50% RH

Clothing		Operative temperature	Relative air velocity m/s							
clo	m² °C/W	°C	< 0,10	0,10	0,15	0,20	0,30	0,40	0,50	1,00
0	0	26	– 1,62	– 1,62	– 1,96	– 2,34				
		27	– 1,00	– 1,00	– 1,36	– 1,69				
		28	– 0,39	– 0,42	– 0,76	– 1,05				
		29	0,21	0,13	– 0,15	– 0,39				
		30	0,80	0,68	0,45	0,26				
		31	1,39	1,25	1,08	0,94				
		32	1,96	1,83	1,71	1,61				
		33	2,50	2,41	2,34	2,29				
0,25	0,039	24	– 1,52	– 1,52	– 1,80	– 2,06	– 2,47			
		25	– 1,05	– 1,05	– 1,33	– 1,57	– 1,94	– 2,24	– 2,48	
		26	– 0,58	– 0,61	– 0,87	– 1,08	– 1,41	– 1,67	– 1,89	– 2,66
		27	– 0,12	– 0,17	– 0,40	– 0,58	– 0,87	– 1,10	– 1,29	– 1,97
		28	0,34	0,27	0,07	– 0,09	– 0,34	– 0,53	– 0,70	– 1,28
		29	0,80	0,71	0,54	0,41	0,20	0,04	– 0,10	– 0,58
		30	1,25	1,15	1,02	0,91	0,74	0,61	0,50	0,11
		31	1,71	1,61	1,51	1,43	1,30	1,20	1,12	0,83
0,50	0,078	23	– 1,10	– 1,10	– 1,33	– 1,51	– 1,78	– 1,99	– 2,16	
		24	– 0,72	– 0,74	– 0,95	– 1,11	– 1,36	– 1,55	– 1,70	– 2,22
		25	– 0,34	– 0,38	– 0,56	– 0,71	– 0,94	– 1,11	– 1,25	– 1,71
		26	0,04	– 0,01	– 0,18	– 0,31	– 0,51	– 0,66	– 0,79	– 1,19
		27	0,42	0,35	0,20	0,09	– 0,08	– 0,22	– 0,33	– 0,68
		28	0,80	0,72	0,59	0,49	0,34	0,23	0,14	– 0,17
		29	1,17	1,08	0,98	0,90	0,77	0,68	0,60	0,34
		30	1,54	1,45	1,37	1,30	1,20	1,13	1,06	0,86
0,75	0,116	21	– 1,11	– 1,11	– 1,30	– 1,44	– 1,66	– 1,82	– 1,95	– 2,36
		22	– 0,79	– 0,81	– 0,98	– 1,11	– 1,31	– 1,46	– 1,58	– 1,95
		23	– 0,47	– 0,50	– 0,66	– 0,78	– 0,96	– 1,09	– 1,20	– 1,55
		24	– 0,15	– 0,19	– 0,33	– 0,44	– 0,61	– 0,73	– 0,83	– 1,14
		25	0,17	0,12	– 0,01	– 0,11	– 0,26	– 0,37	– 0,46	– 0,74
		26	0,49	0,43	0,31	0,23	0,09	0,00	– 0,08	– 0,33
		27	0,81	0,74	0,64	0,56	0,45	0,36	0,29	0,08
		28	1,12	1,05	0,96	0,90	0,80	0,73	0,67	0,48
1,00	0,155	20	– 0,85	– 0,87	– 1,02	– 1,13	– 1,29	– 1,41	– 1,51	– 1,81
		21	– 0,57	– 0,60	– 0,74	– 0,84	– 0,99	– 1,11	– 1,19	– 1,47
		22	– 0,30	– 0,33	– 0,46	– 0,55	– 0,69	– 0,80	– 0,88	– 1,13
		23	– 0,02	– 0,07	– 0,18	0,27	– 0,39	– 0,49	– 0,56	– 0,79
		24	0,26	0,20	0,10	0,02	– 0,09	– 0,18	– 0,25	– 0,46
		25	0,53	0,48	0,38	0,31	0,21	0,13	0,07	– 0,12
		26	0,81	0,75	0,66	0,60	0,51	0,44	0,39	0,22
		27	1,08	1,02	0,95	0,89	0,81	0,75	0,71	0,56

Prediction of Thermal Comfort

- Comfort zones
  - defined using isotherms parallel to Effective Temp.
  - 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, $22.8\ ^{o}C \leq SET \leq 26.1\ ^{o}C$
    - for winter, $20.0\ ^{o}C \leq SET \leq 23.9\ ^{o}C$

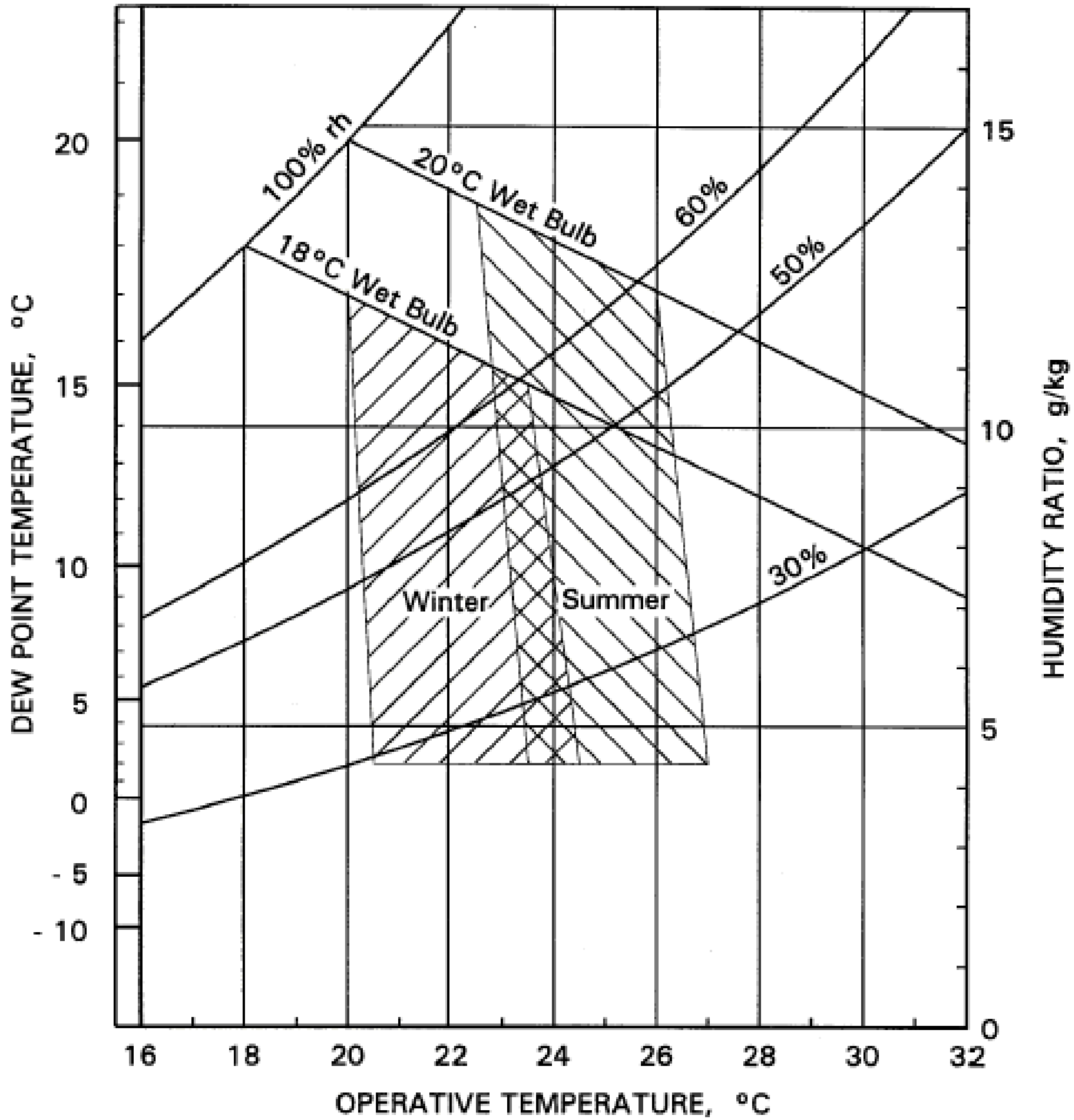
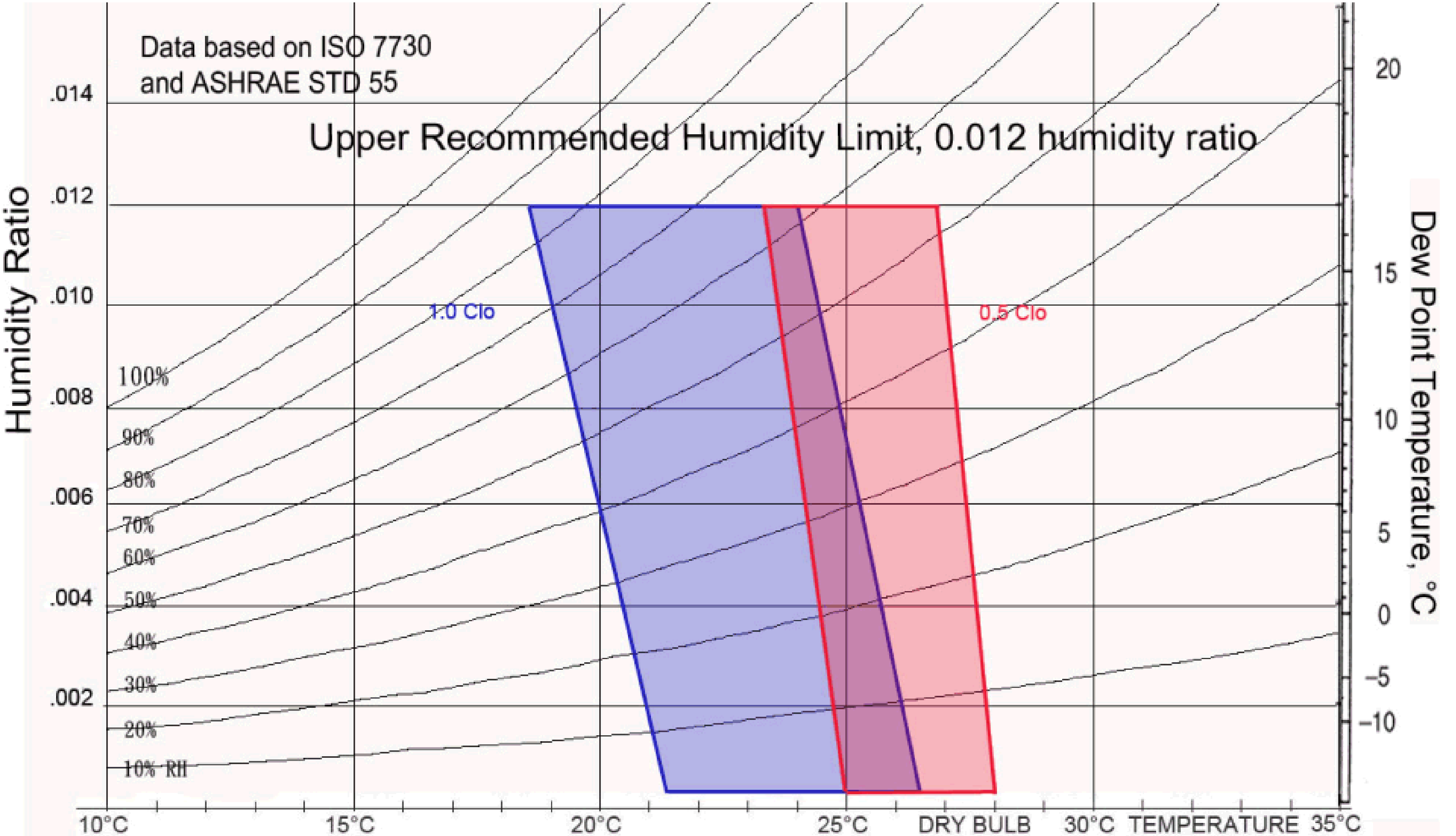


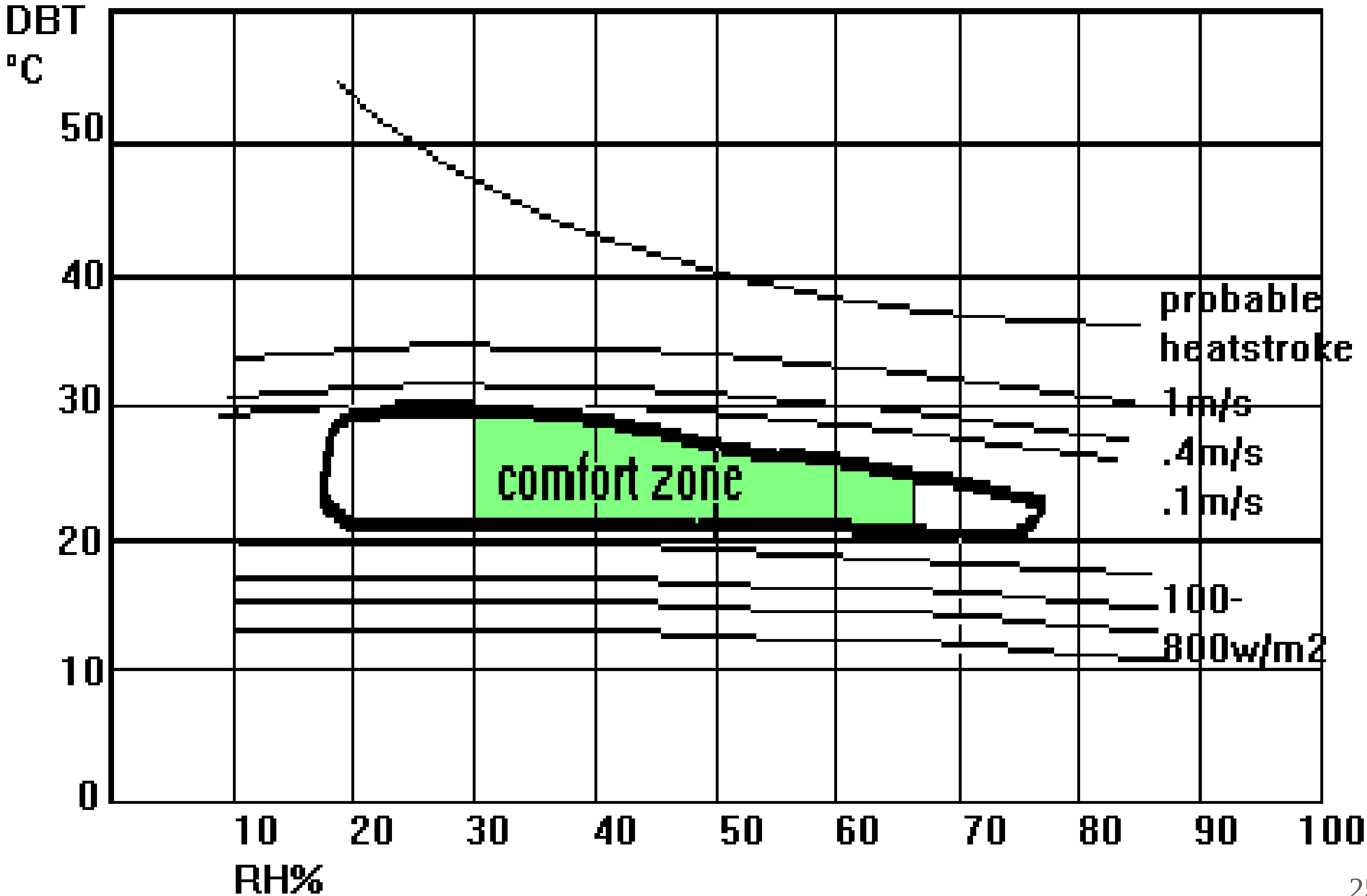
Fig. 5 ASHRAE Summer and Winter Comfort Zones

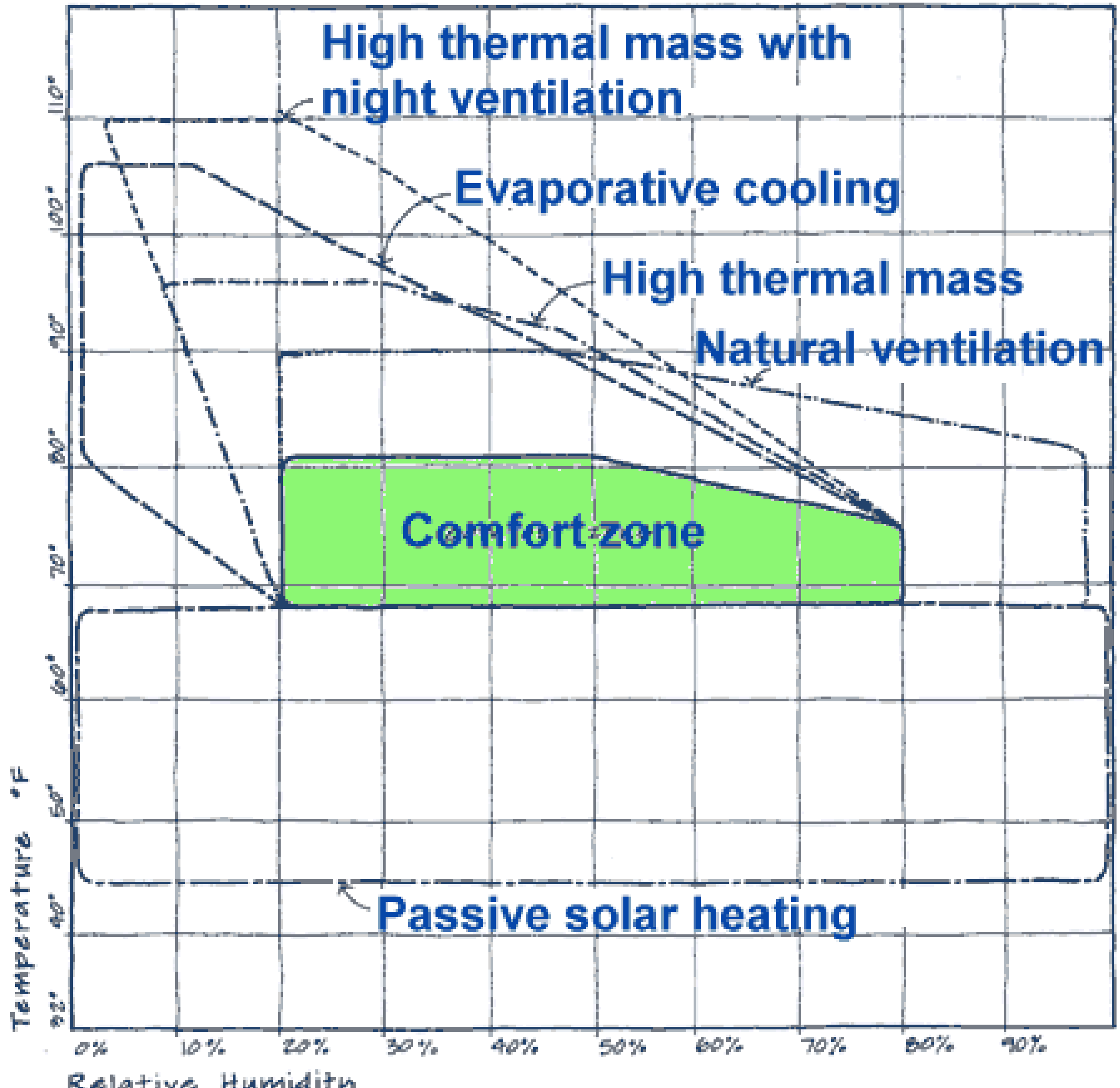
(Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during primarily sedentary activity.)

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



Olgyays bioclimatic chart





Bioclimatic Chart with Design Strategies

Influencing Factors

- Environmental factors:
  - Dry-bulb temperature
  - Relative humidity (or water vapour pressure)
    - Influences evaporative heat loss and skin wettedness
    - Usually RH between 30% and 70% is comfortable
  - Air velocity (increase convective heat loss)
    - Preferable air velocity = 0.2m/s (a base for most assumptions)
  - Mean radiation temperature
    - Radiation has great effect on thermal sensation

Influencing Factors

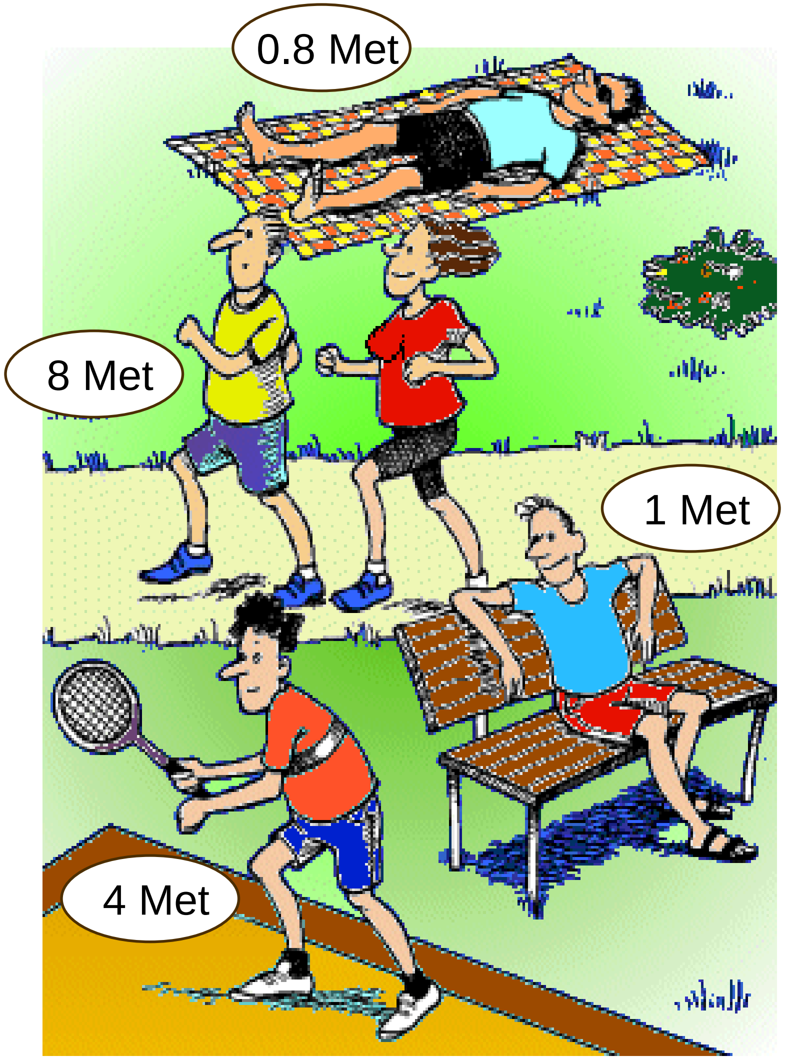
- Other factors affecting comfort:
  - Age
    - Sensation of old people and younger people
  - Adaptation
    - People in warm climates may adapt to hot environment
  - Sex
    - Women: lower skin temperature, evaporative loss & lower met rate
    - Clothing and perferrence of temperature

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 1.8 m^2.
- A sitting person in thermal comfort will have a heat loss of ~105W.
- 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

1.1 Met

6.5 Met

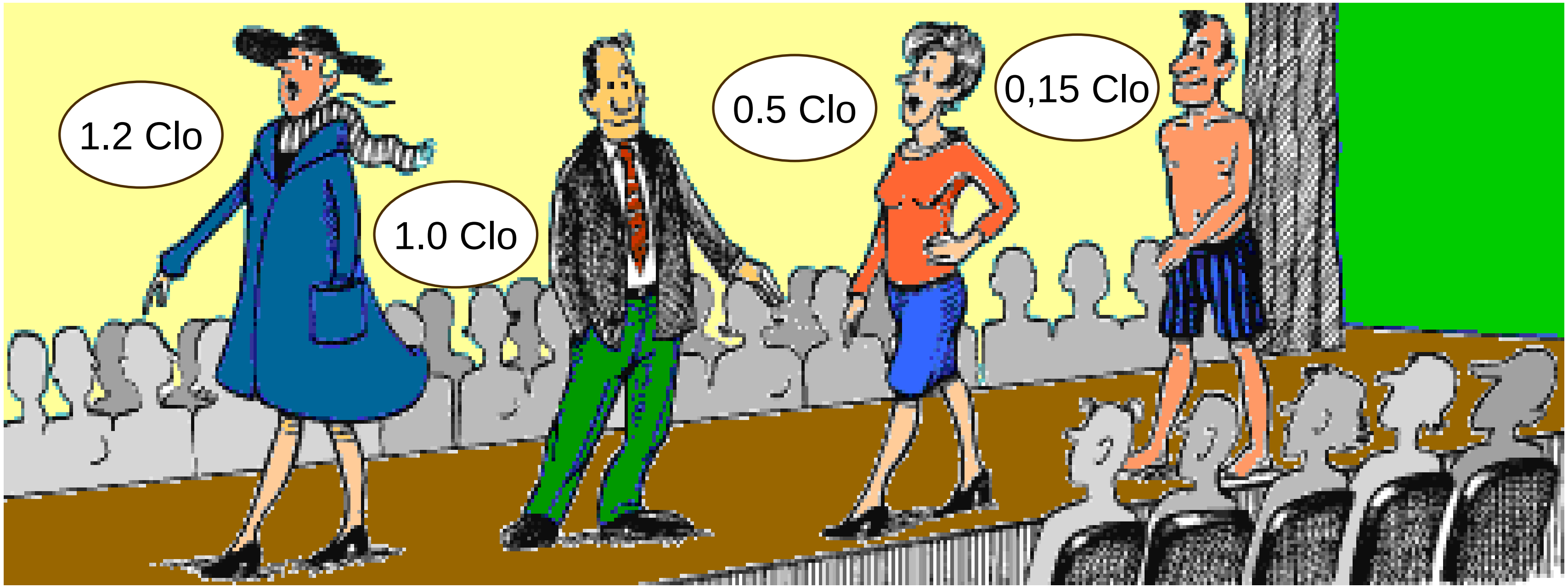
2.5 Met

ASHRAE Standard 55-2004

Metabolic Rates for Typical Tasks

Activity	Met Units	Metabolic Rate W/m²	Metabolic Rate (Btu/h·ft²)
Resting			
Sleeping	0.7	40	(13)
Reclining	0.8	45	(15)
Seated, quiet	1.0	60	(18)
Standing, relaxed	1.2	70	(22)
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	(37)
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	(48)
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	(70)
Office Activities			
Seated, reading, or writing	1.0	60	(18)
Typing	1.1	65	(20)
Filing, seated	1.2	70	(22)
Filing, standing	1.4	80	(26)
Walking about	1.7	100	(31)
Lifting/packing	2.1	120	(39)
Driving/Flying			
Automobile	1.0-2.0	60-115	(18-37)
Aircraft, routine	1.2	70	(22)
Aircraft, instrument landing	1.8	105	(33)
Aircraft, combat	2.4	140	(44)
Heavy vehicle	3.2	185	(59)
Miscellaneous Occupational Activities			
Cooking	1.6-2.0	95-115	(29-37)
House cleaning	2.0-3.4	115-200	(37-63)
Seated, heavy limb movement	2.2	130	(41)
Machine work			
sawing (table saw)	1.8	105	(33)
light (electrical industry)	2.0-2.4	115-140	(37-44)
heavy	4.0	235	(74)
Handling 50 kg (100 lb) bags	4.0	235	(74)
Pick and shovel work	4.0-4.8	235-280	(74-88)
Miscellaneous Leisure Activities			
Dancing, social	2.4-4.4	140-255	(44-81)
Calisthenics/exercise	3.0-4.0	175-235	(55-74)
Tennis, single	3.6-4.0	210-270	(66-74)
Basketball	5.0-7.6	290-440	(92-140)
Wrestling, competitive	7.0-8.7	410-505	(129-160)

Calculation of Insulation in Clothing



- 1 Clo = Insulation value of 0.155 $m^2\ ^oC/W$

Clo Values Table

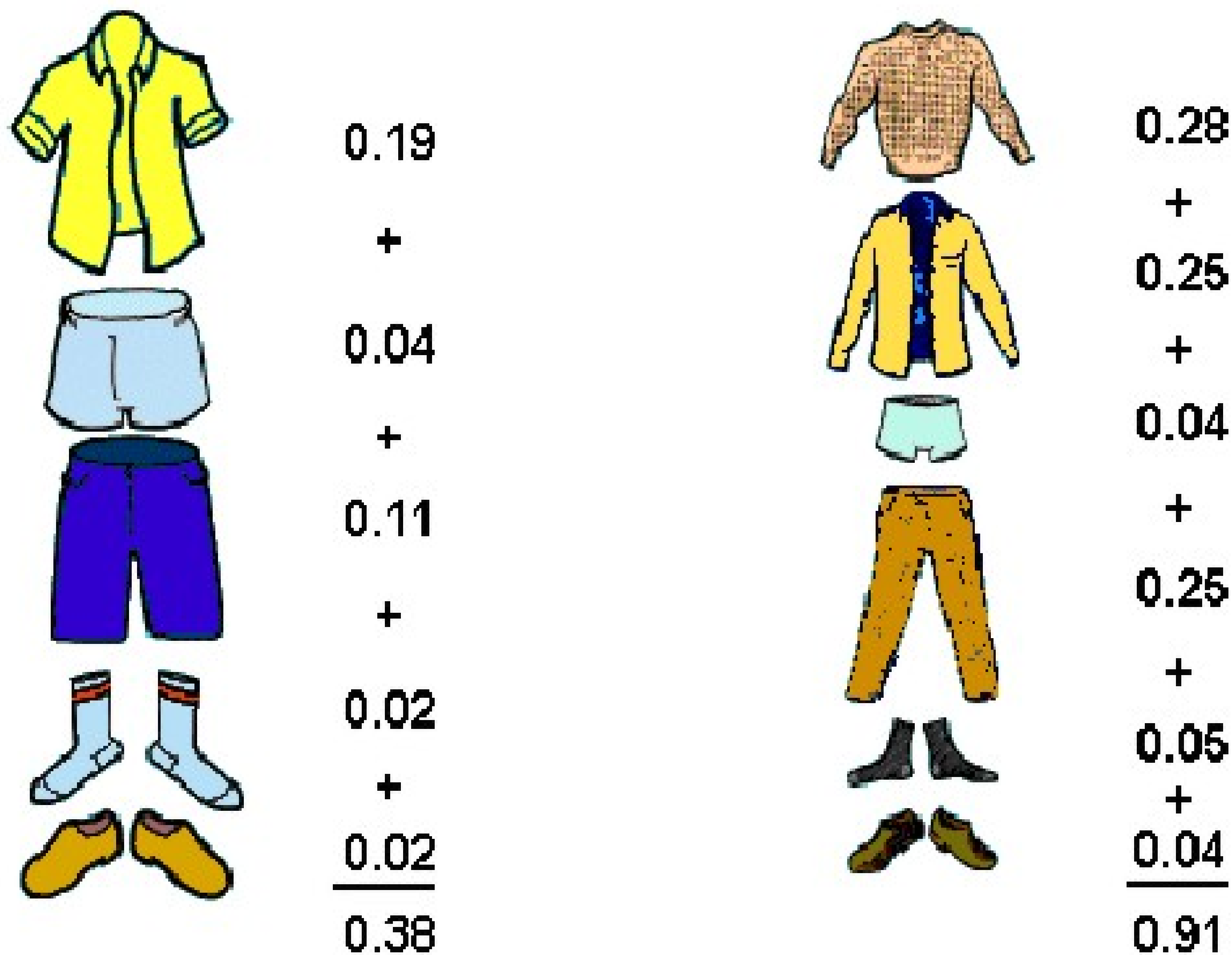
Garment description		I_{clu} Clo	I_{clu} m^2 °C/W
Underwear	Pantyhose Briefs Pants long legs	0.02 0.04 0.10	0.003 0.006 0.016
Underwear, shirts	Bra T-shirt Half-slip, nylon	0.01 0.09 0.14	0.002 0.014 0.022
Shirts	Tube top Short sleeves Normal, long sleeves	0.06 0.09 0.25	0.009 0.029 0.039
Trousers	Shorts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

Clo Values Table

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

Calculation of Clo-value (Clo)

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

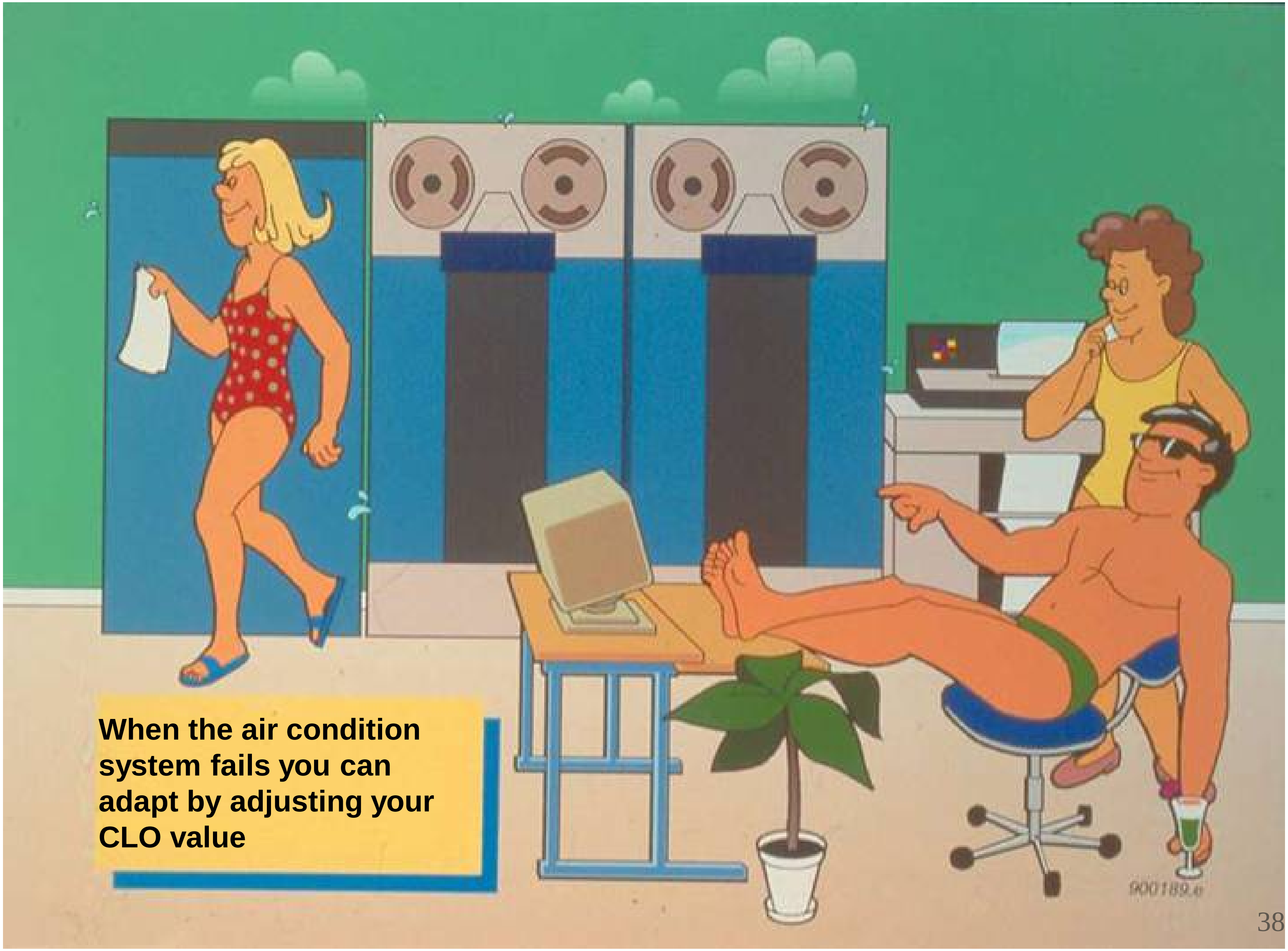


Things to consider when calculation the CLO value

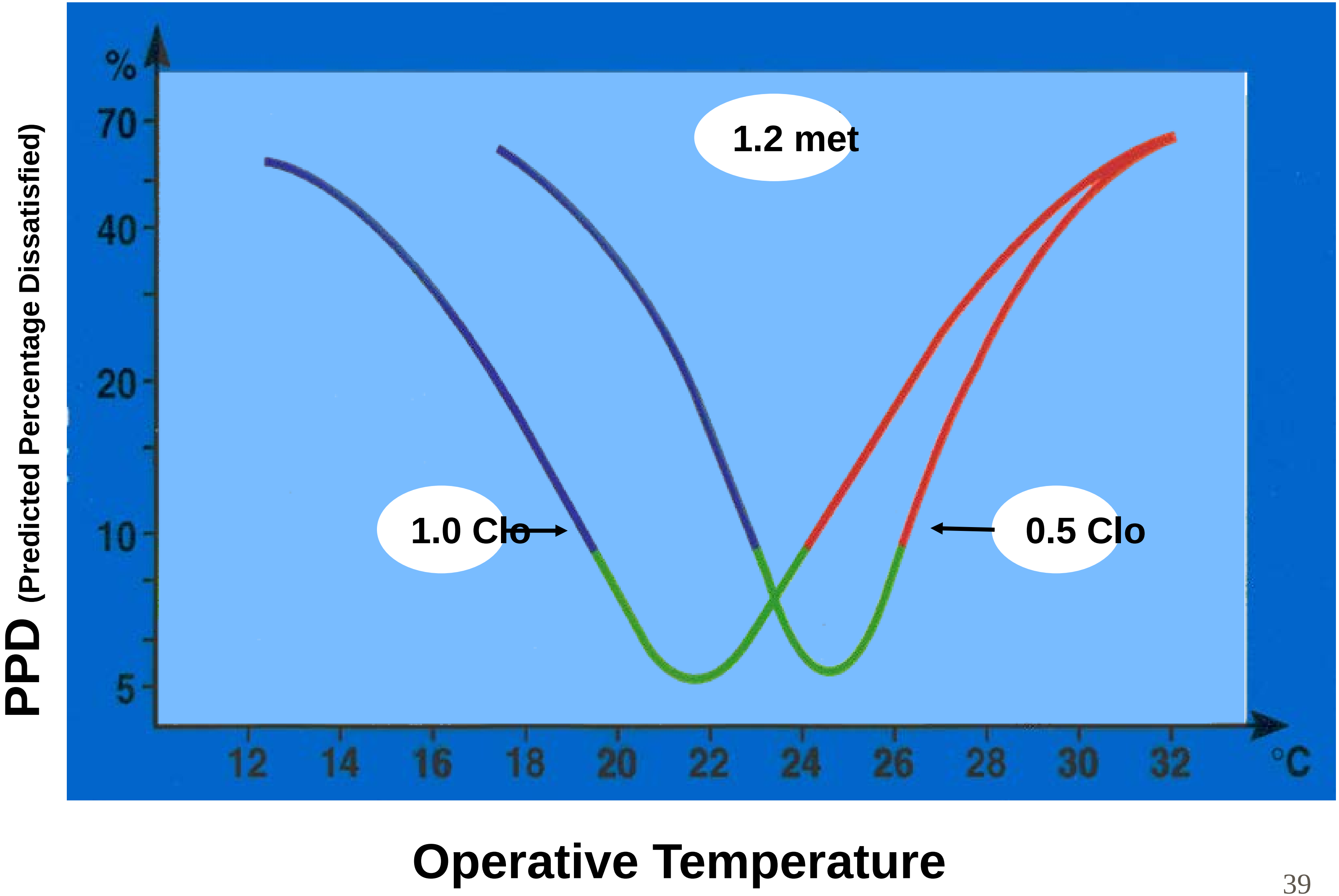
Thermal insulation of chairs

Insulation of wet clothing

Acclimatisation/Adaptation!



Adjustment of Clo Value

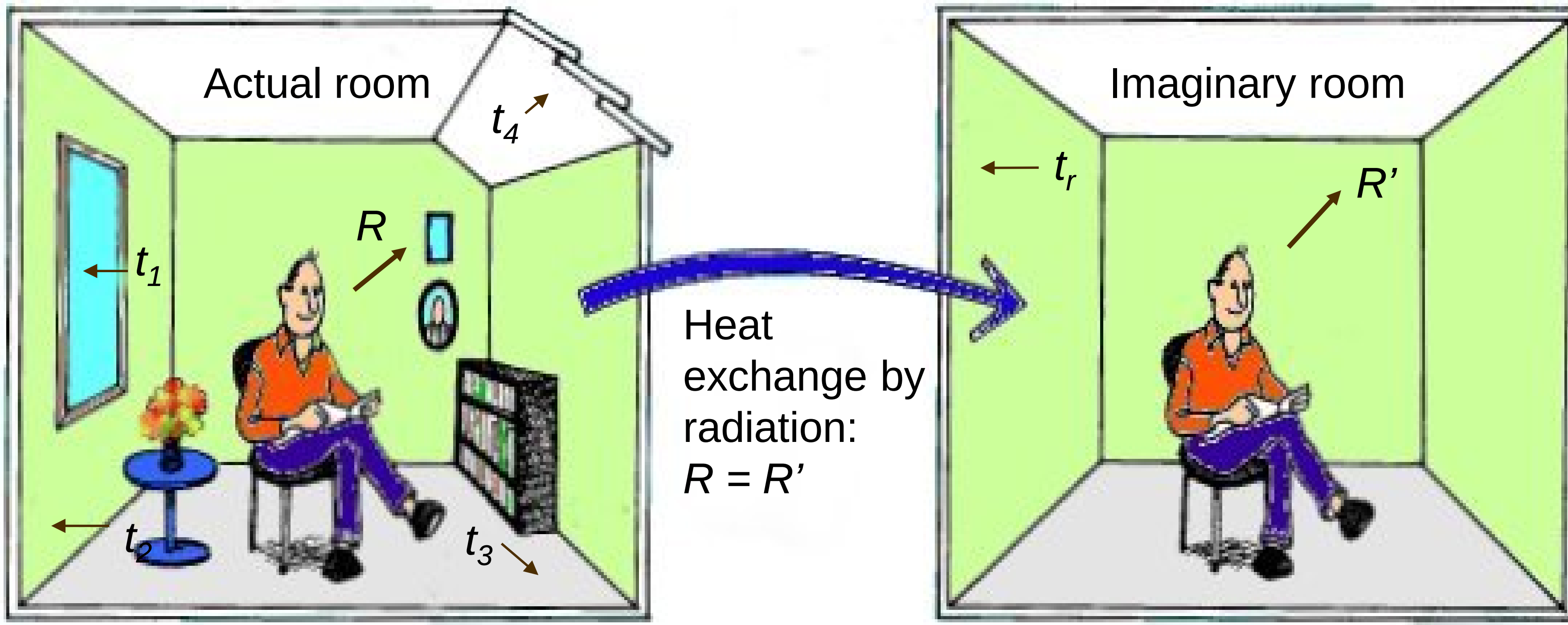


What should be measured?

- 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** (ASHRAE 55-2004)
  - 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

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

  - In practical cases (v < 0.2m/s, difference between t_{db} and t_r < 4°C),

$$t_o = \frac{t_r + t_{db}}{2}$$

  - In higher velocities, $t_o = (1 - A)t_r + At_{db}$,
    where A = 0.6 (v = 0.2 - 0.6m/s), 0.7 (v = 0.6 – 1.0m/s)

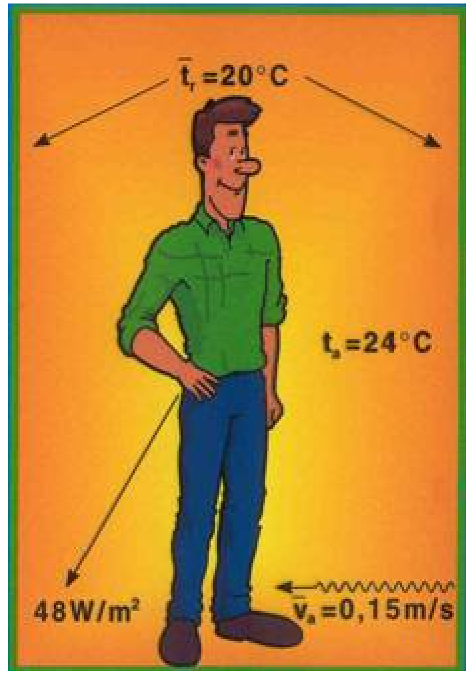
Environmental Indices

- **Effective temperature, *ET*** (ASHRAE 55-1992)
  - 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)”

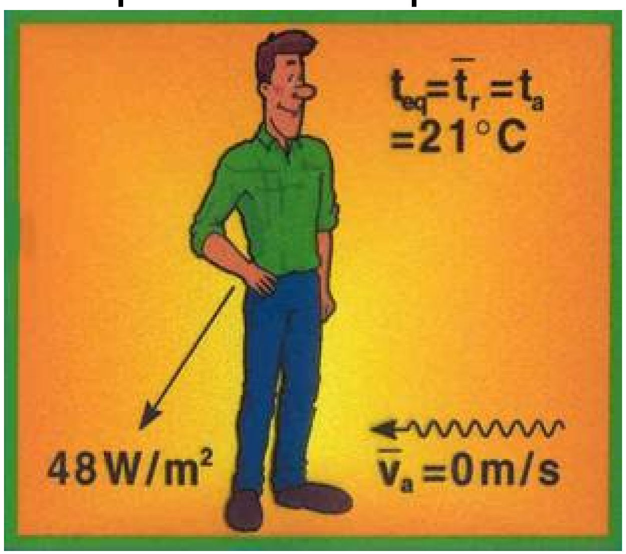
Environmental Indices

- **Equivalent 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)

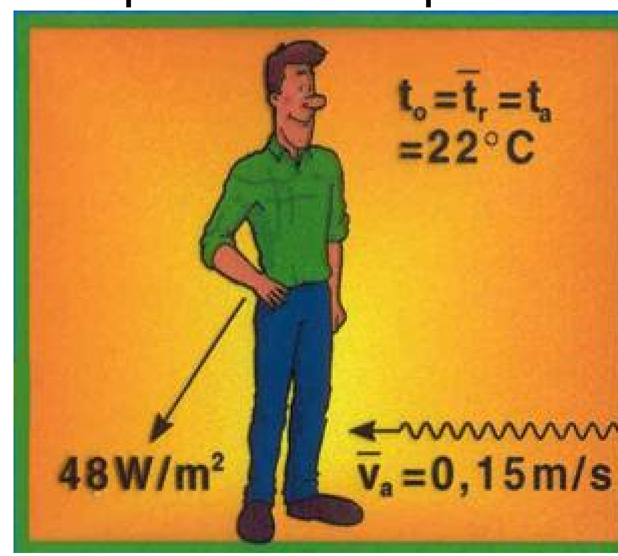
Operative and Equivalent Temperature



Operative temperature



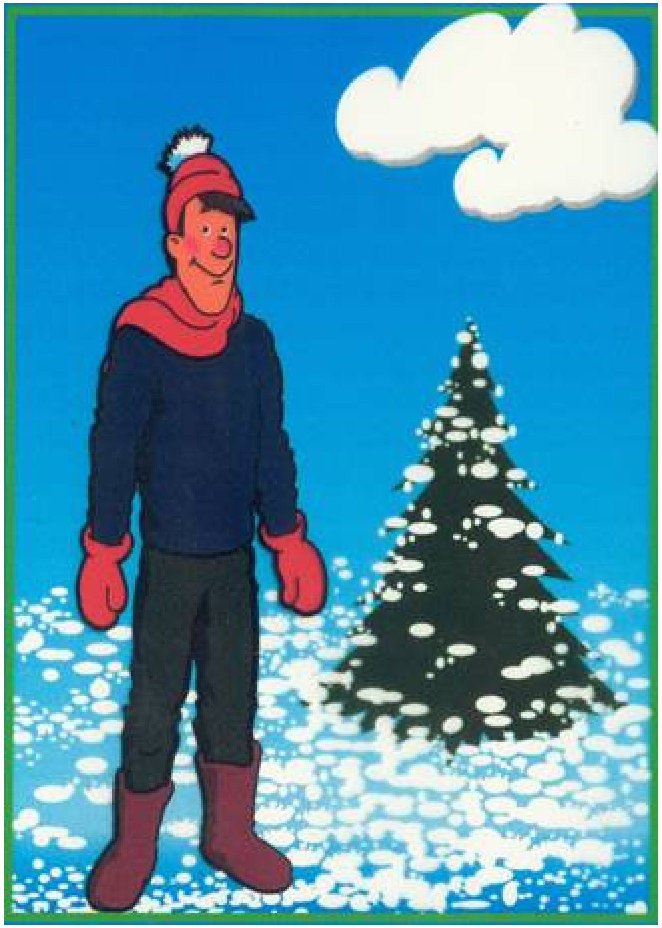
Equivalent temperature



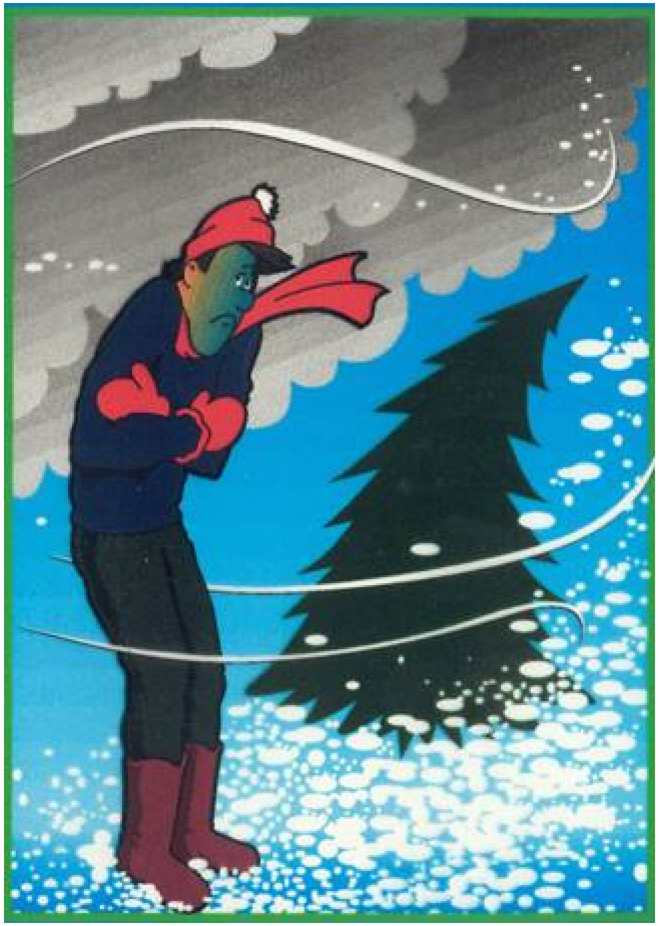
Combines DBT & MRT

Combines DBT, MRT & air velocity

Operative and Equivalent Temperature



Operative temperature

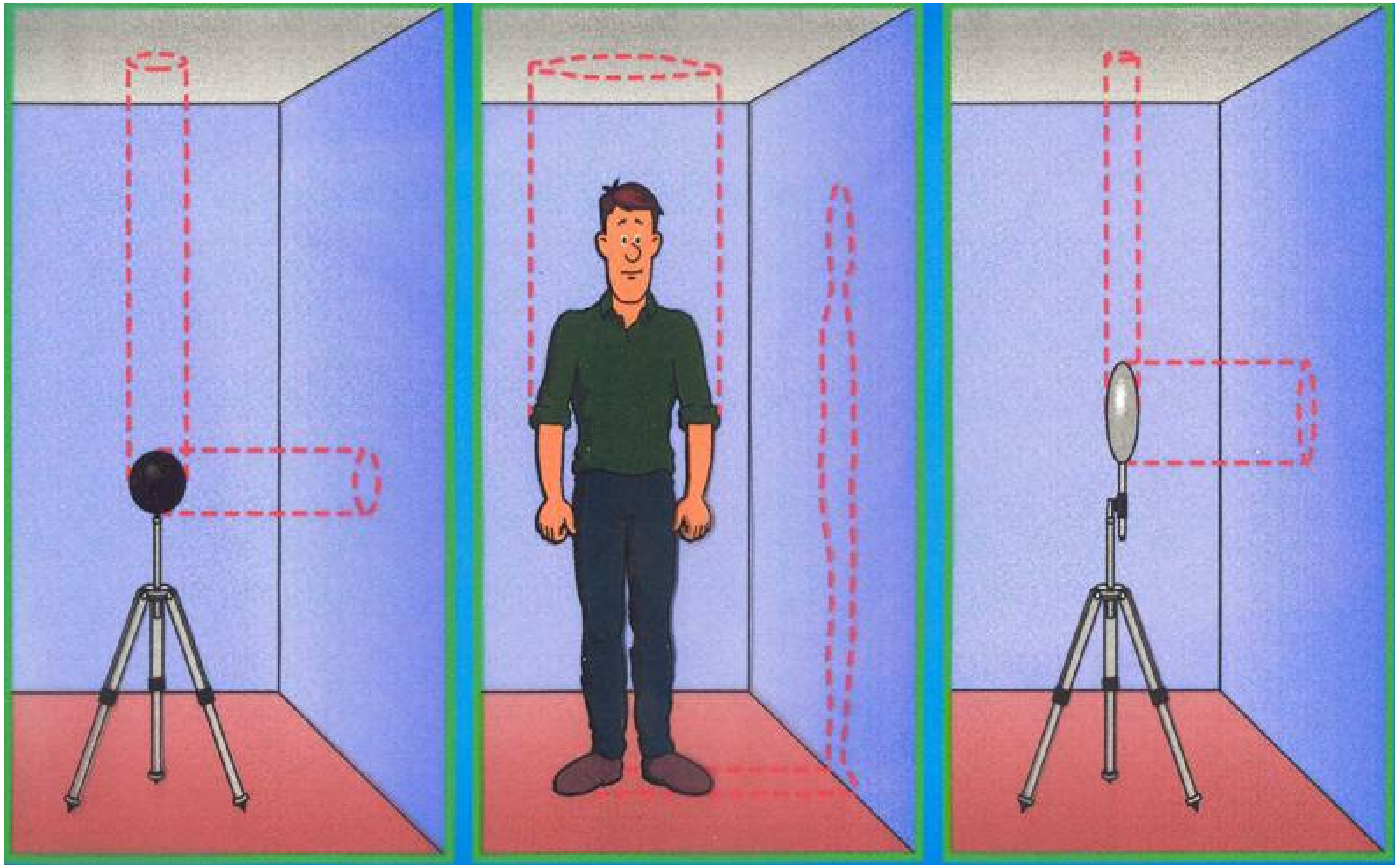


Equivalent temperature

Combines DBT & MRT

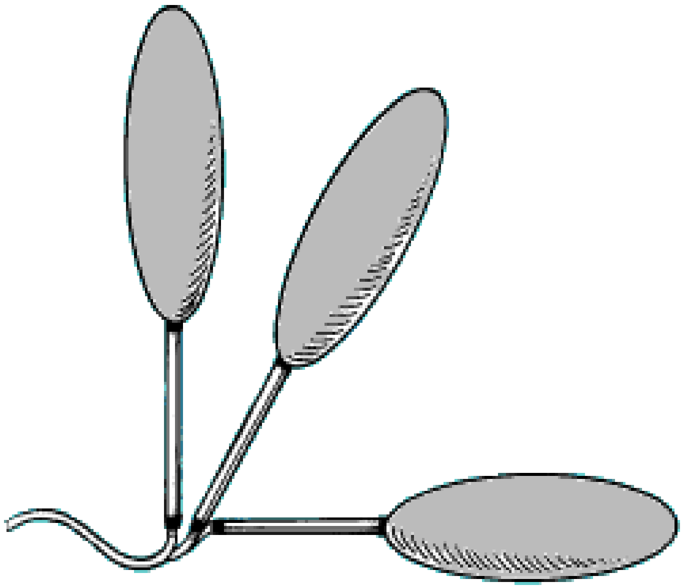
Combines DBT, MRT & air velocity

Projected area factor



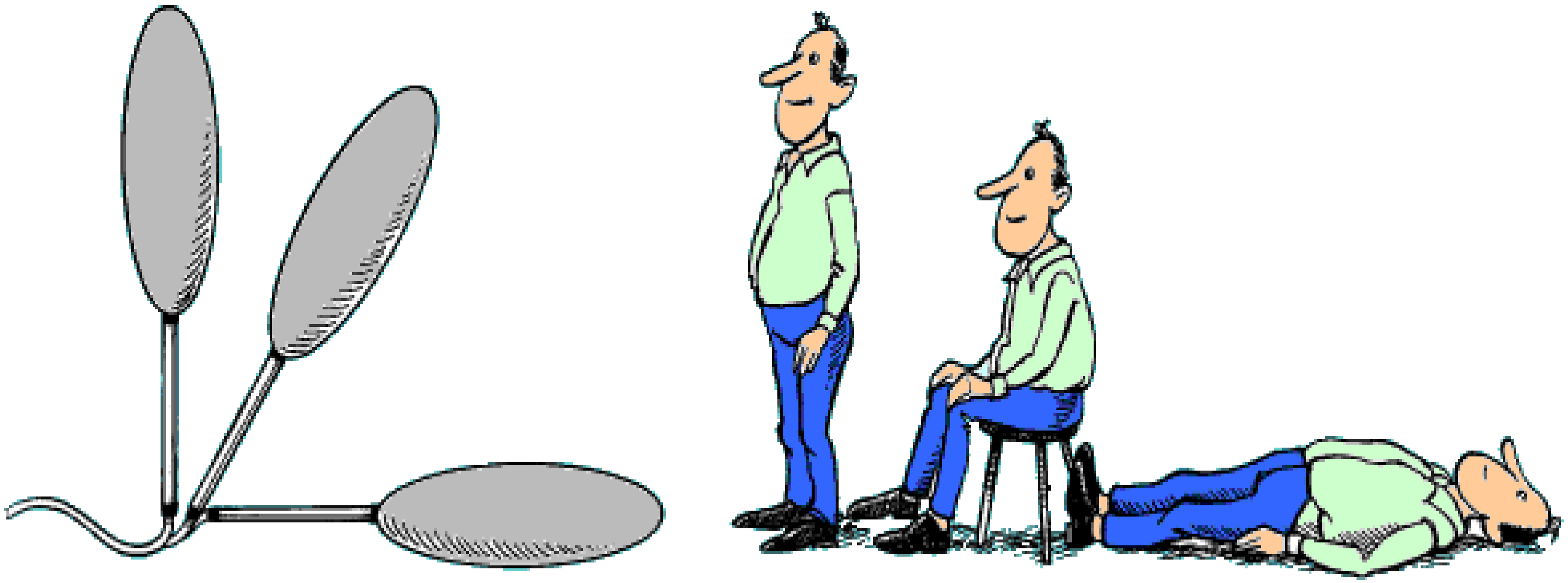
$\bar{t}_r = 20\ °C$ $\bar{t}_r = 20\ °C$ $\bar{t}_r = 20\ °C$

Operative Temperature



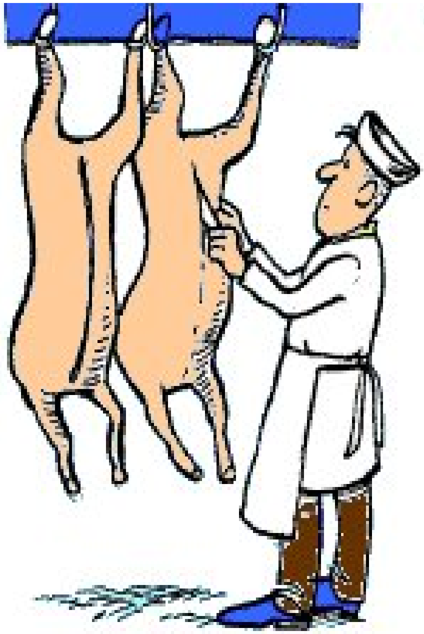
- The Operative temperature $\bar{t}_o$ integrates the effect of t_a and t_r
- Measure Operative Temperature: the transducer must have same heat exchange properties as an unheated mannequin (artificial human) dummy.

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)

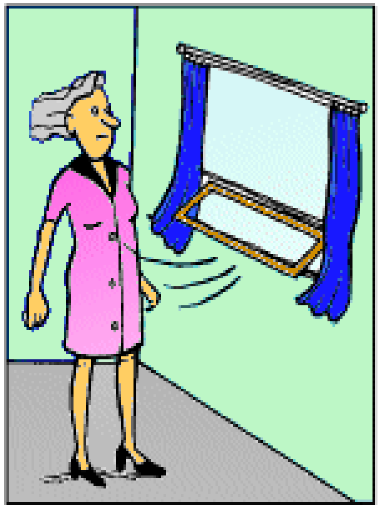


1.7 clo
2.5 Met
RH=50%
t_{co}=6°C

0.8 clo
2.2 Met
RH=50%
t_{co}=18°C

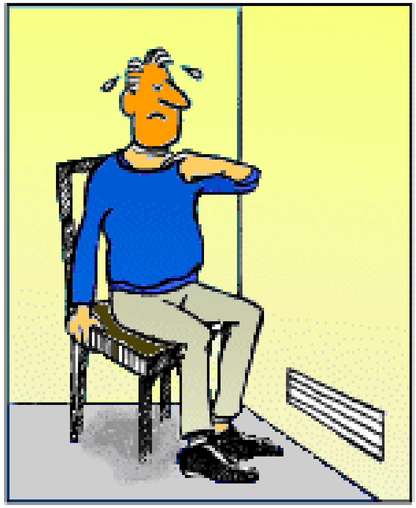
0.5 clo
1.2 Met
RH=50%
t_{co}=24.5°C

Local Thermal Discomfort

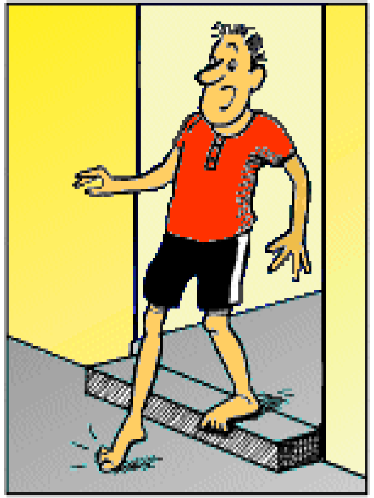


- Draught

- Radiation Asymmetry

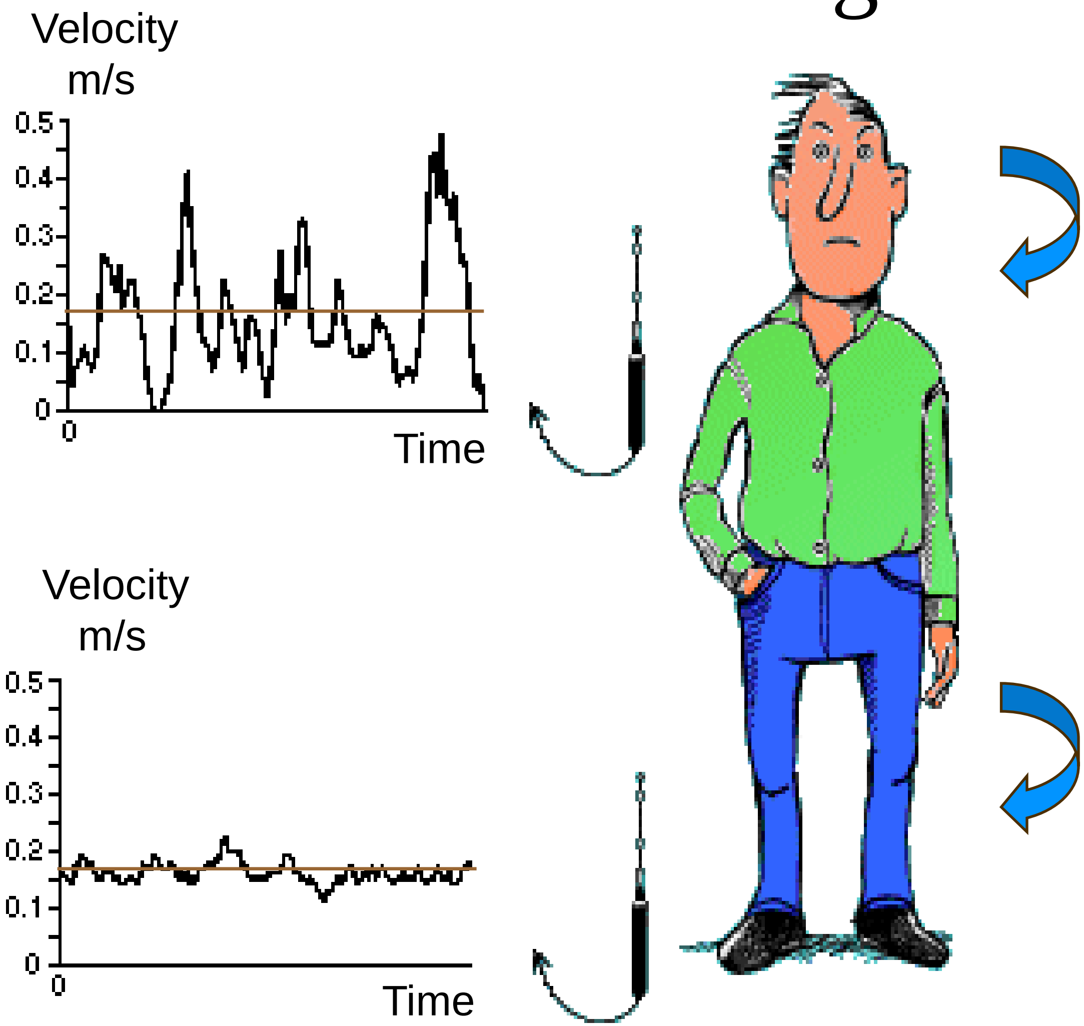


- Vertical Air Temperature Differences.



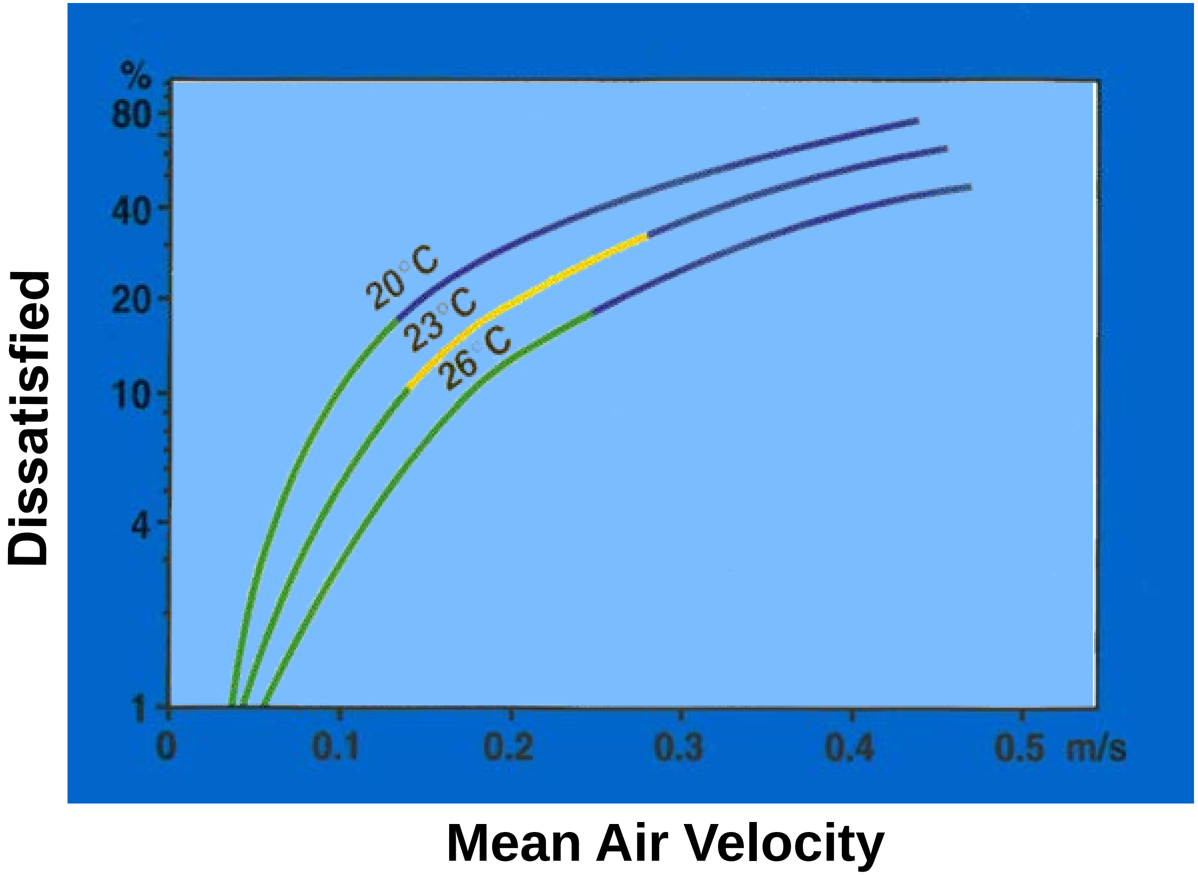
- Floor temperature

Draught



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

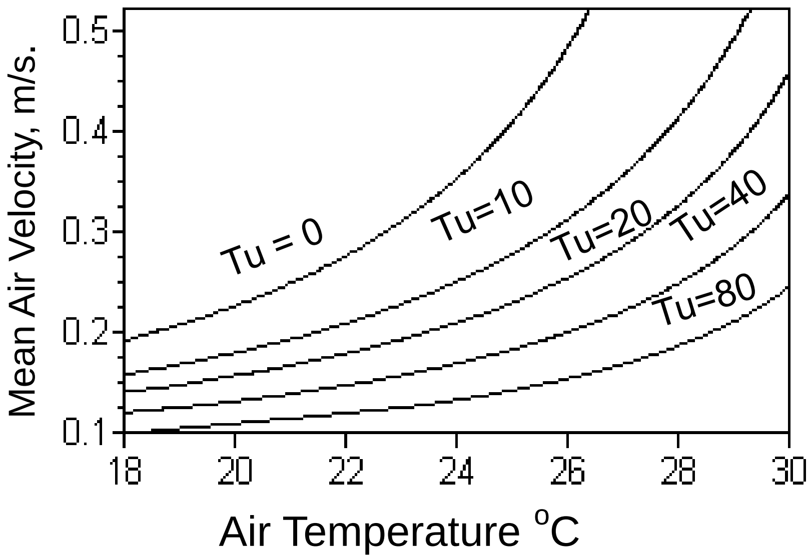
Draught



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

Evaluating Draught Rate

15% dissatisfied

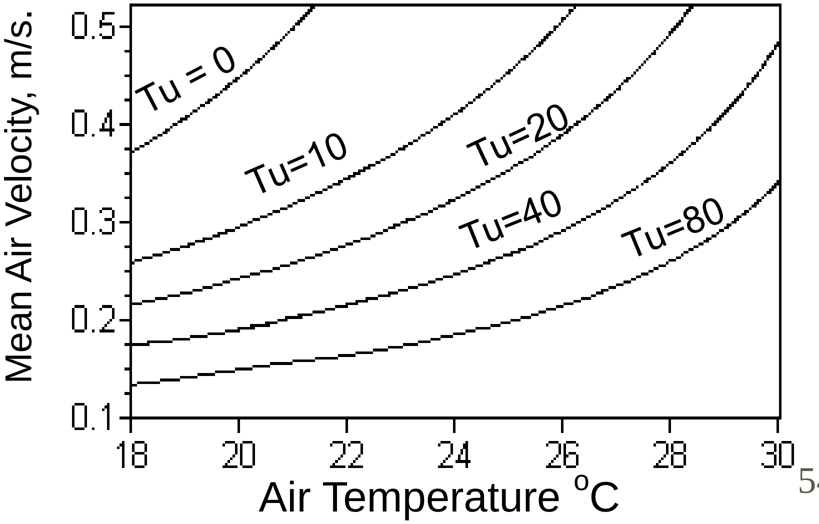


- Fluctuations in Air Velocity is described by Turbulence Intensity (Tu)
- Draught Rate equation is based on studies of 150 people, and stated in ISO 7730

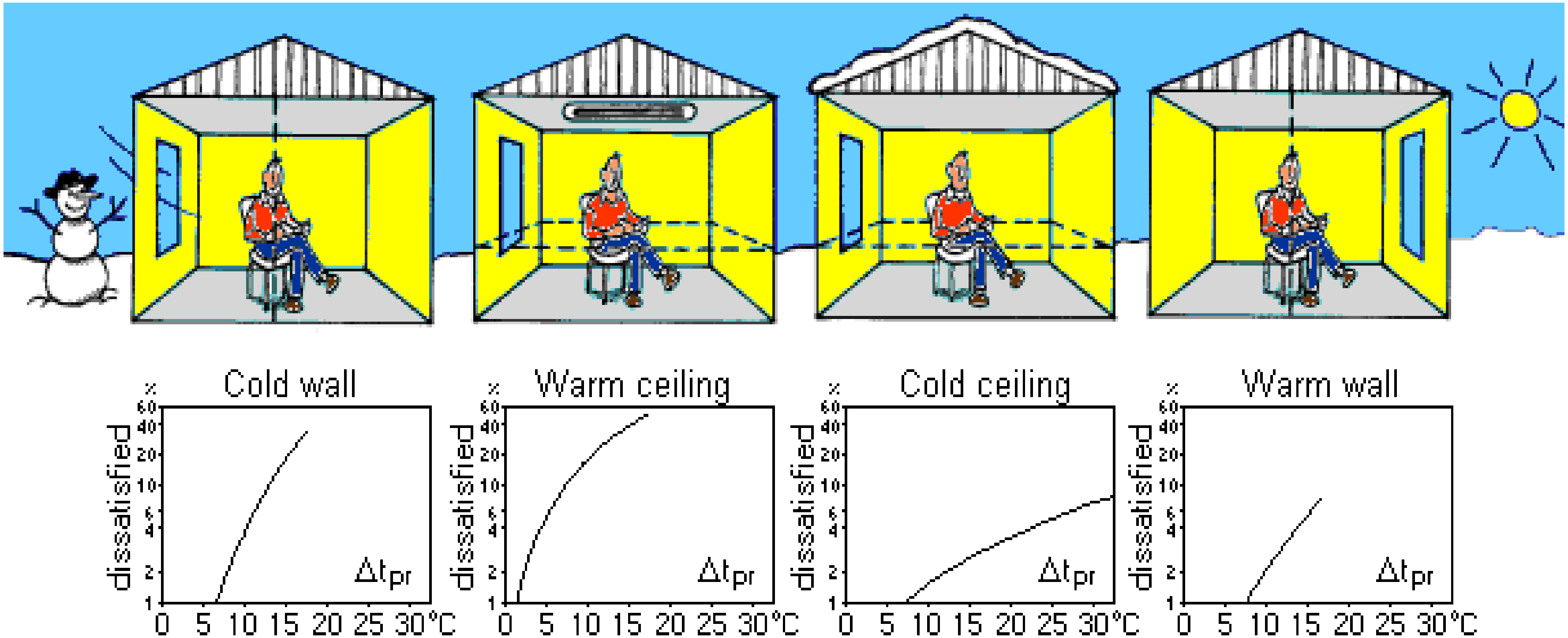
Turbulent Intensity (*Tu*)
The ratio of the standard deviation of the air speed (SD_v) to the mean air speed (v)

Draft Rate (DR)
Percentage of people predicted to be dissatisfied due to draft

25% dissatisfied

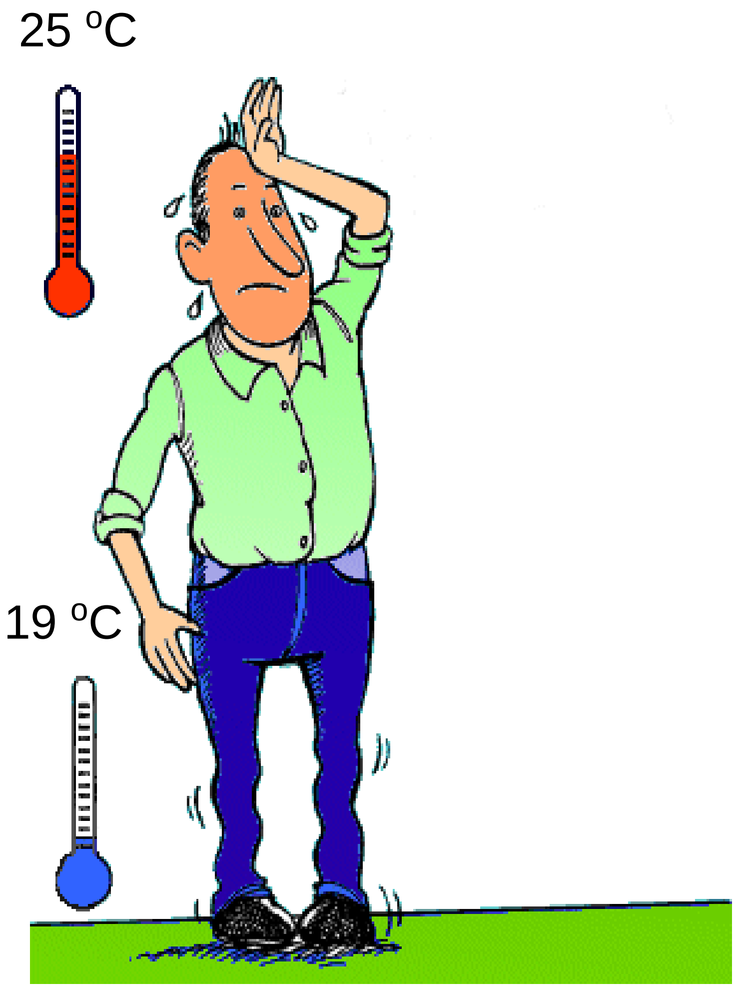


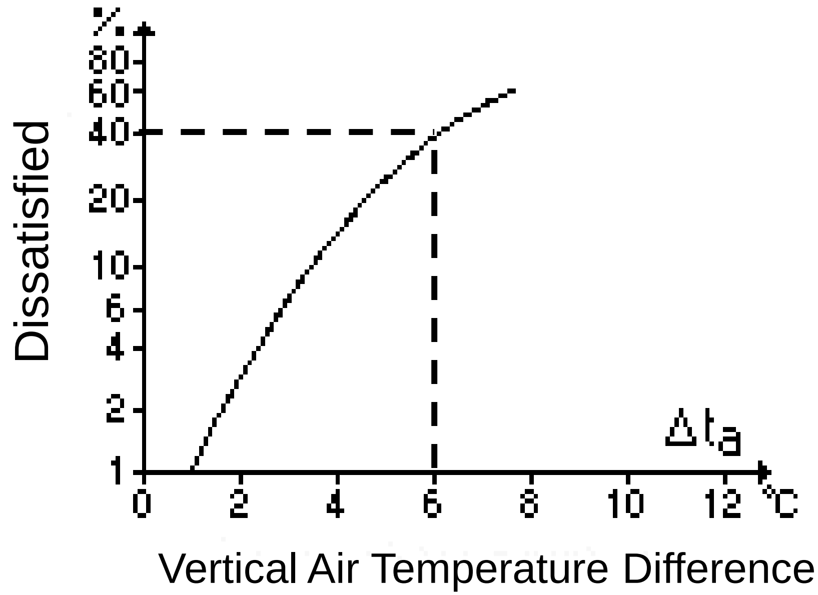
Radiation Asymmetry



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

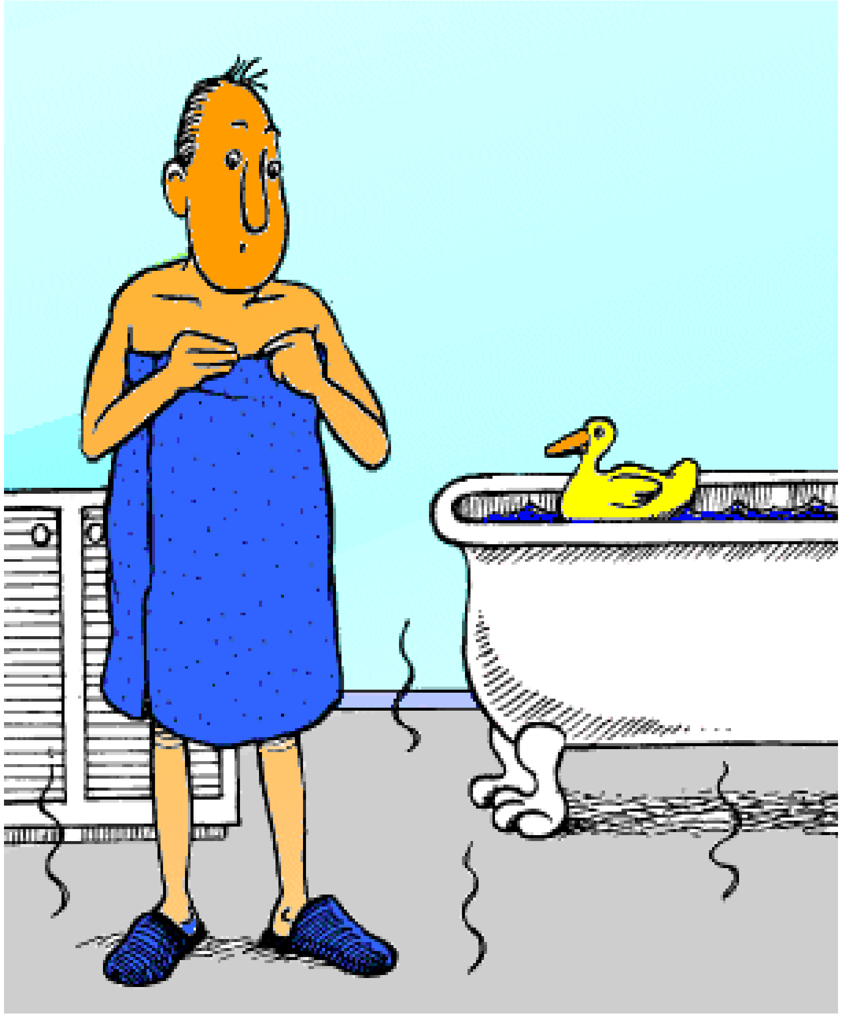
Vertical Air Temperature Difference

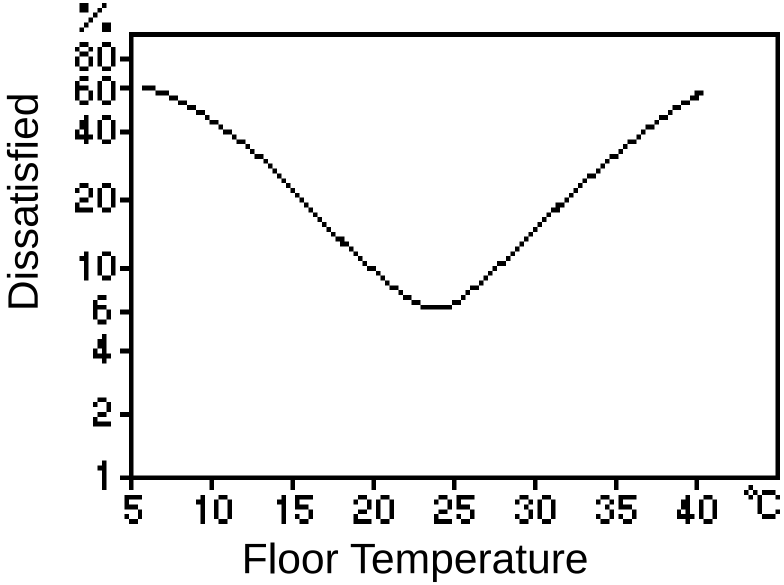




- Vertical Air Temperature Difference is the difference between Air Temperature at ankle and neck level

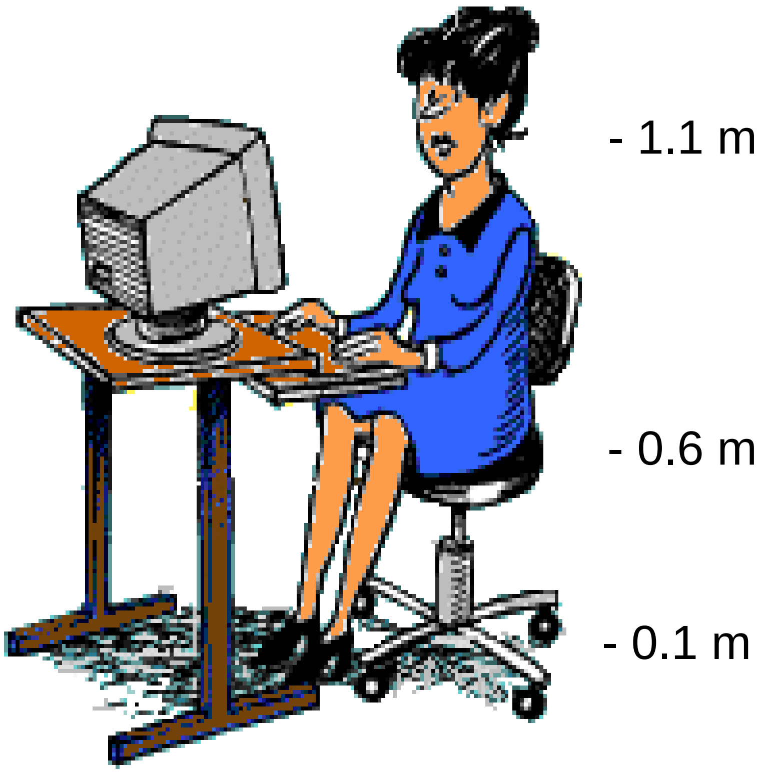
Floor Temperature

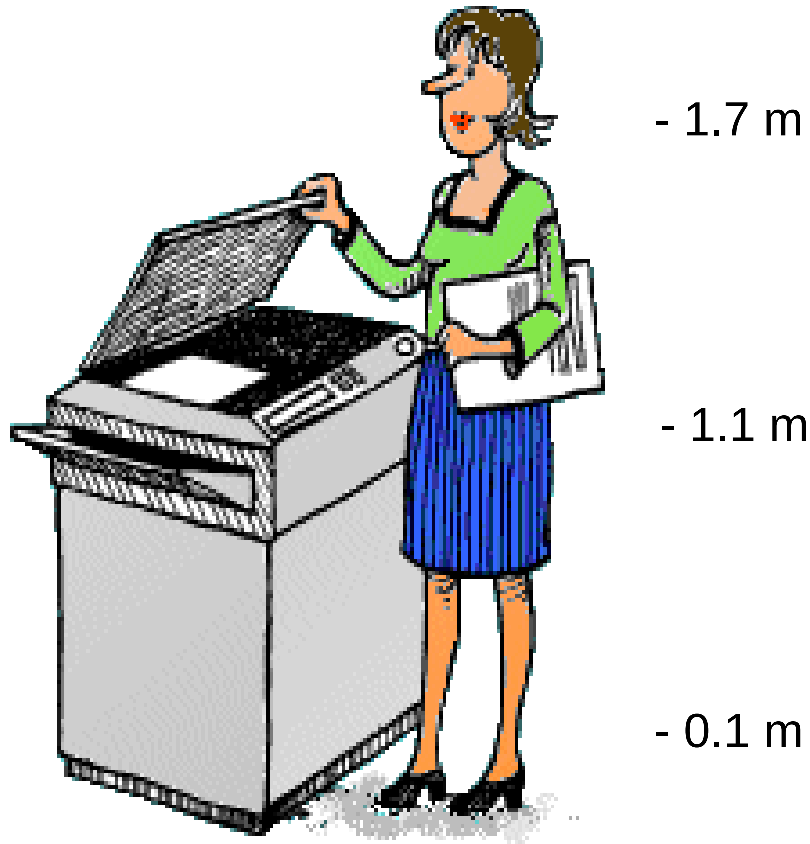




- Acceptable floor temperatures ranging from 19 to 29 ^{o}C
- The graph is made on the assumption that people wear "normal indoor footwear"

Workplace Measurements





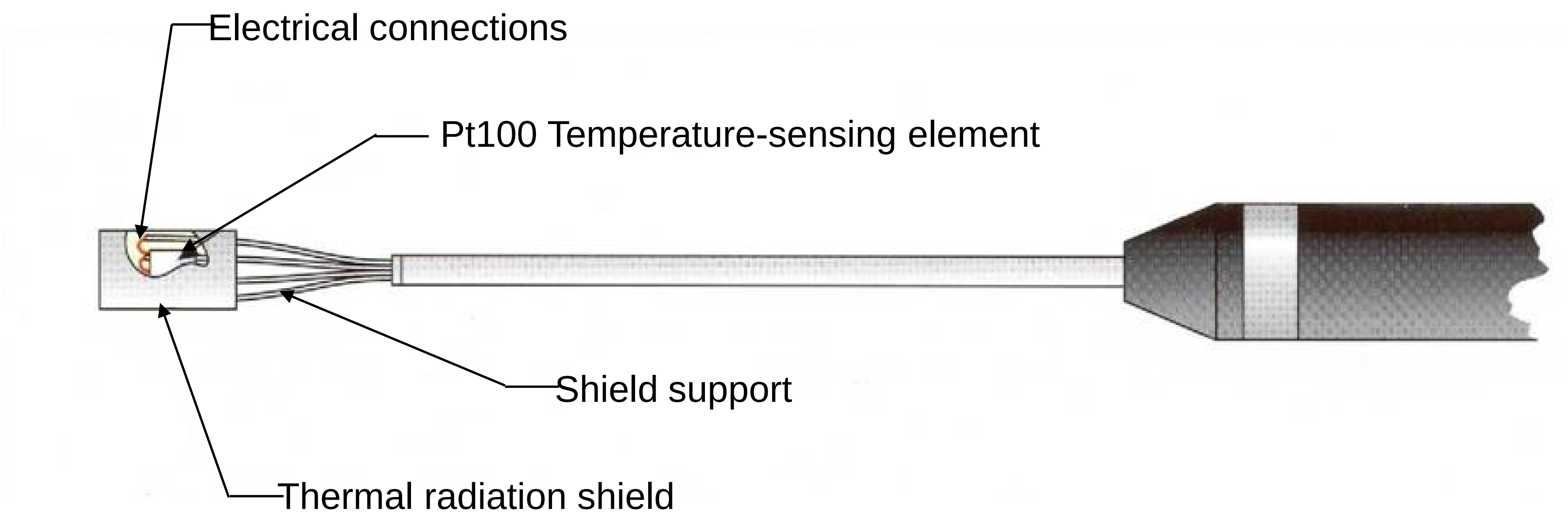
- Measurements of Vertical Temp. difference and Draught at ankle and neck
- Other measurements should be performed at persons centre of gravity

Collection of Thermal Comfort Data

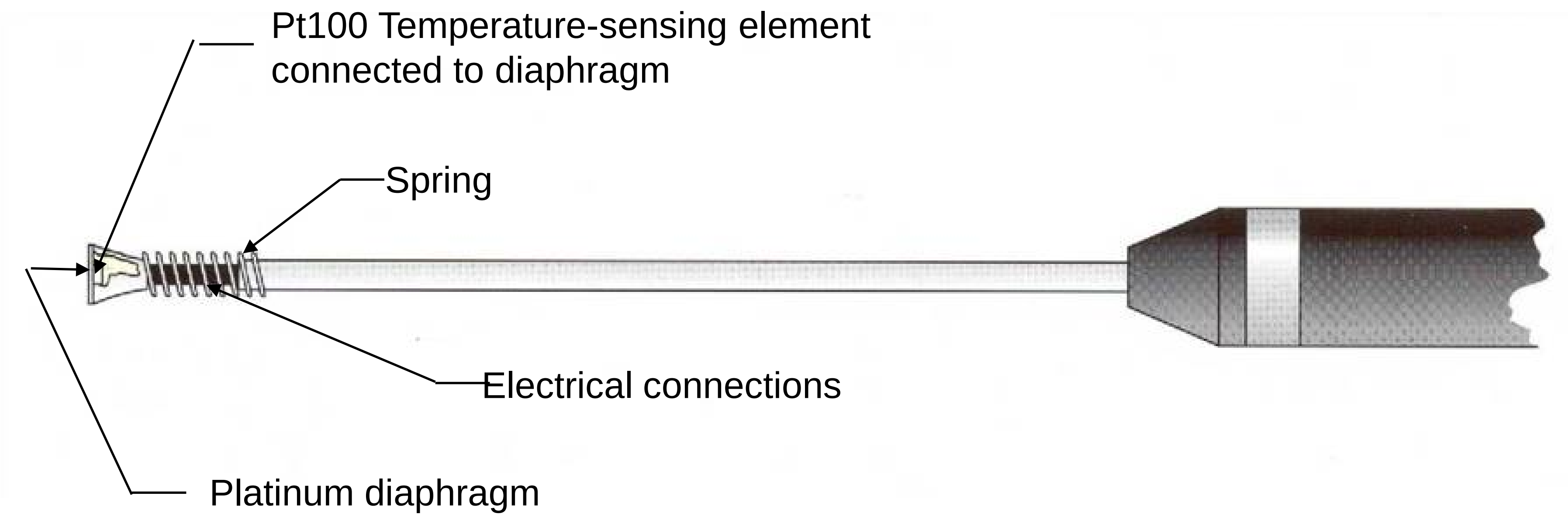
Transducers

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

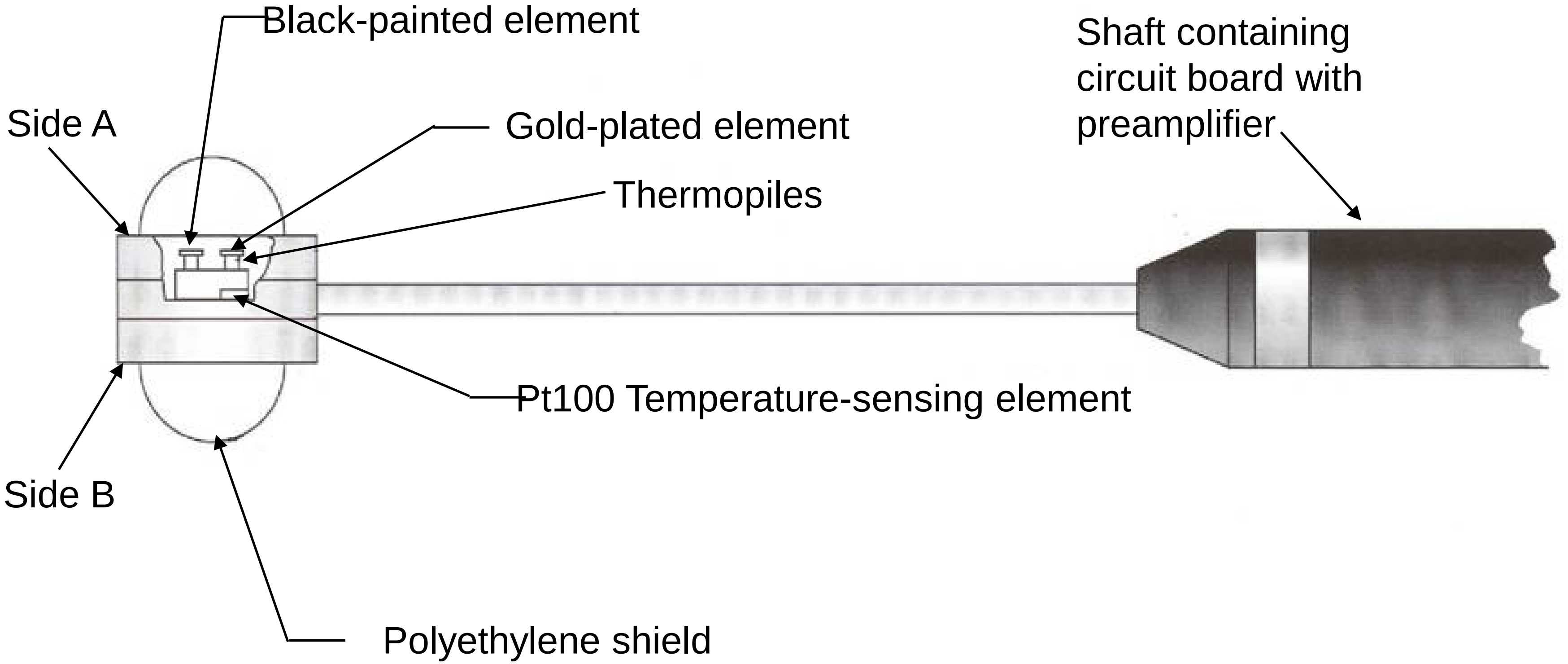
Air Temperature Transducer



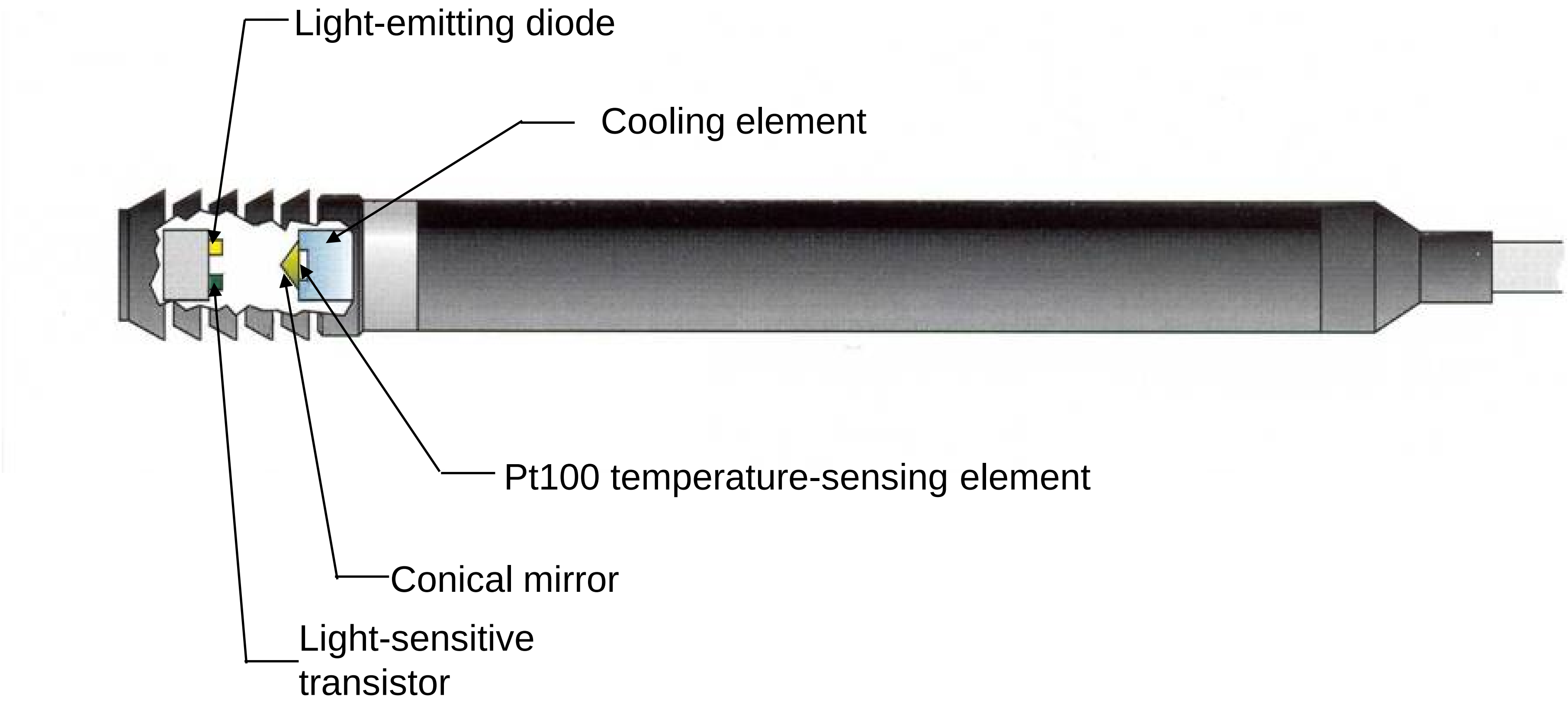
Surface Temperature Transducer



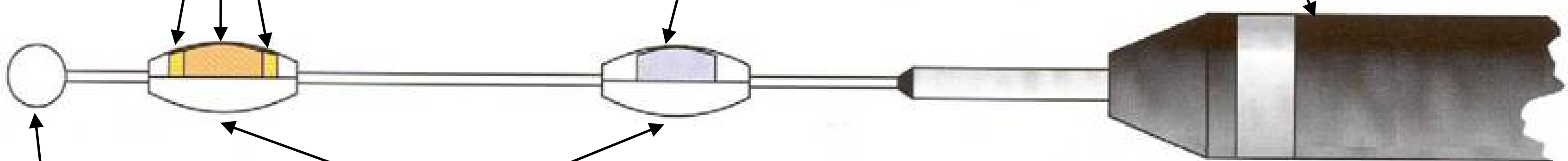
Radiant Temperature Asymmetry Transducer



Humidity Transducer



Air Velocity Transducer



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/