Physical agents
Thermal stress, thermal comfort

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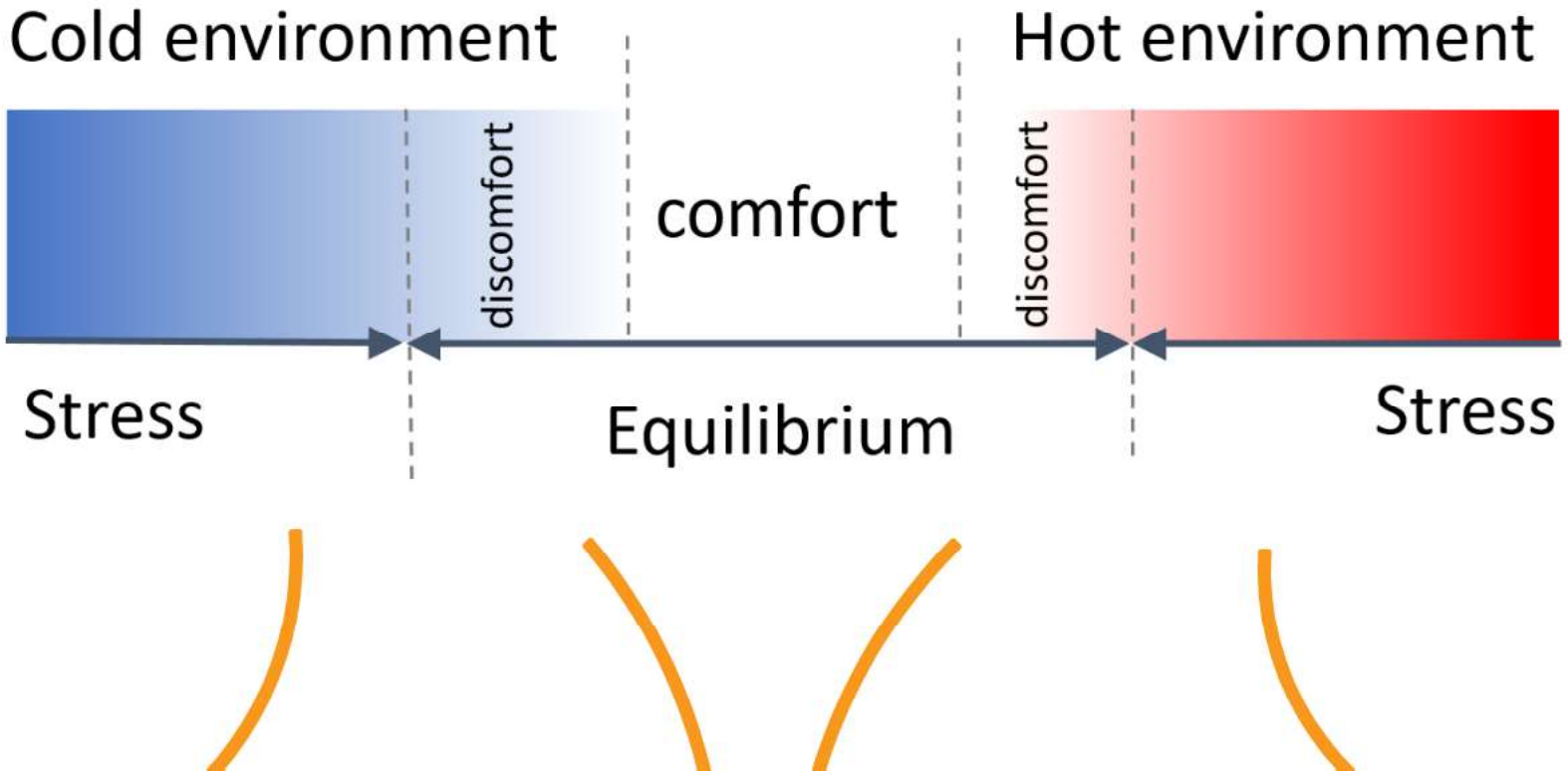
Balance and thermal imbalance

Maintaining thermal equilibrium in environments of varying temperature and humidity (homeothermy)



Heat stress situations

Extreme thermal situations

- Specific heat sources: foundries, glass factories, bakeries, kitchens, chemical industries...
- Containment: underground work, protective equipment
- Physical activities during a period of extreme heat

Heatwave periods

Long lasting heat over several days
In Switzerland:

- 30 -35°C during the day
- 20-25°C at night
- 3 consecutive days

Populations at risk

Workers

% of EU workers exposed to particularly hot or cold environments

	permanently exposed	exposed >25 of the time
Cold exposure	4	21
Hot exposure	6	23

Vulnerable populations

Elderly, young children, people with mental illness, drug and alcohol abusers

Heat balance

Thermal balance: equivalence between internal heat production and external losses

$$H = C_{res} + E_{res} + K + C + R + E$$

H: internal heat production
Cres: convection in the respiratory tract
Eres: evaporation from the respiratory tract
K: conduction at skin level
C: convection at skin level
R : radiation at skin level
E : evaporation from the skin

Heat balance, determining factors

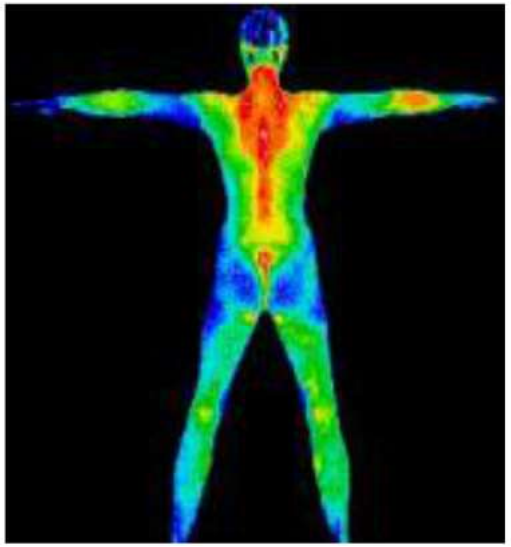
Exposure time
All parameters influencing heat exchange

Temperature of air, of the contact surfaces
Convection, conduction, evaporation $\sim \Delta T$

Temperature of nearby hot surfaces
radiation $\sim \Delta T^4$

Relative humidity $\sim \Delta P_{H_2O}$
Evaporation, convection

Air speed $\sim \sqrt{V}$
Forced convection



Heat balance, determining factors

Individual-related determinants

Physical activity

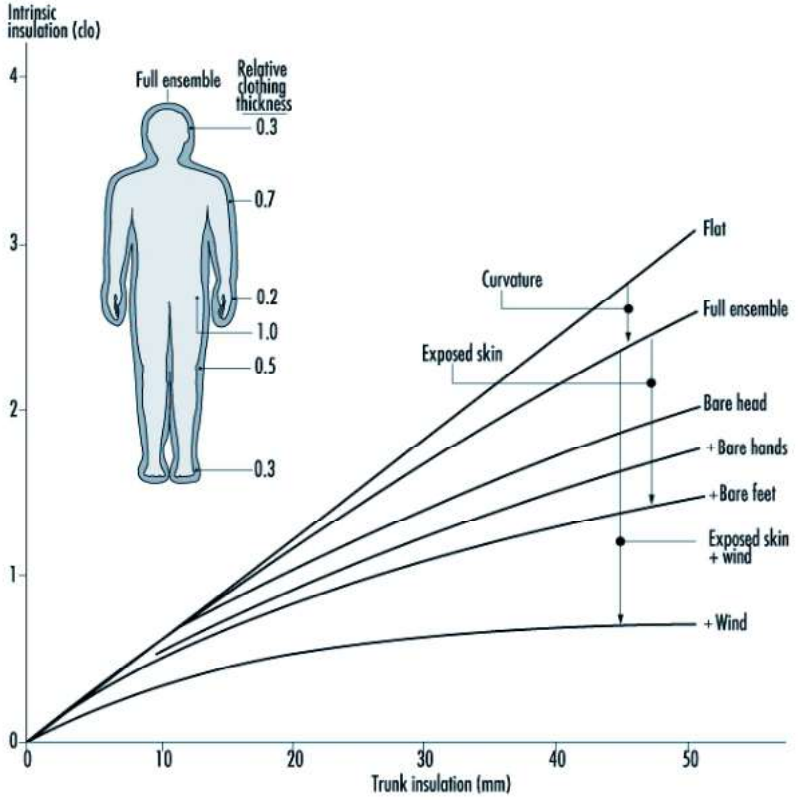
Metabolism: heart rate, body temperature, ...

Thermal insulation

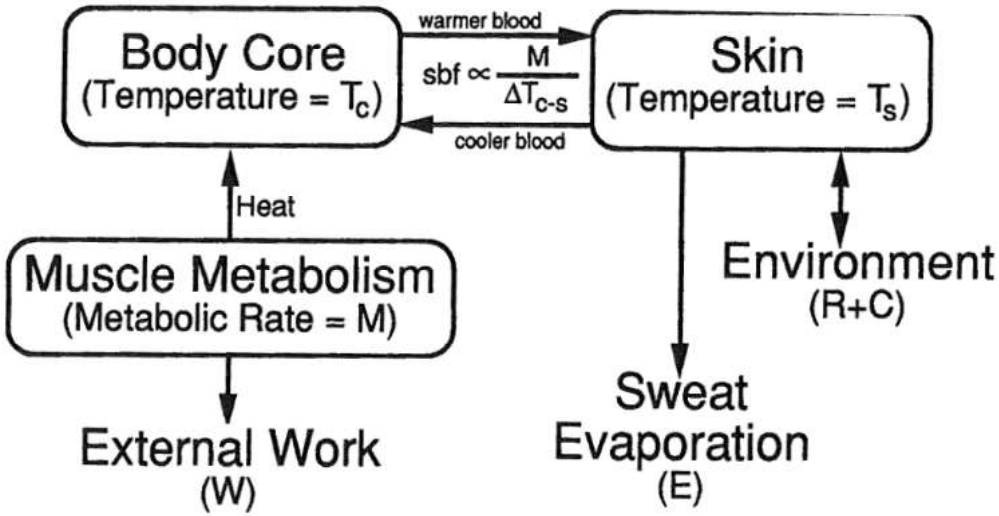
clothing: [clo]

1 clo= 0.155 °C m2 W-1

Clothing	Insulation [clo]
T-shirt	0.09
Light skirt	0.15
Knitting	0.28
Coat	0.6
Boots	0.1



Heat balance, example



Heat exchange model

Typical thermal environments

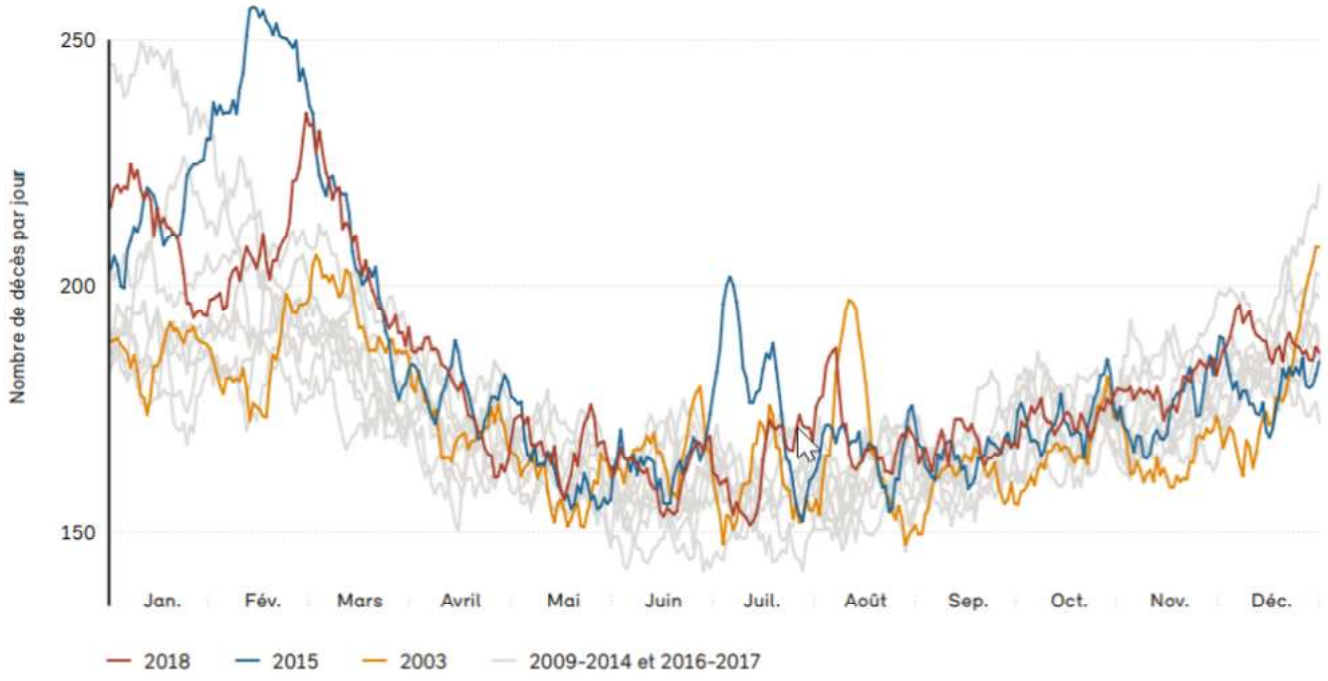
	Situation 1	Situation 2
Wind	1 m/s	1 m/s
T air	20°C	35°C
T rad	25°C	63°C
Metabolism	300 W	300 W
required sweat flow	**144 g/h**	**823 g/h**

Effects of heat stress

Local
swelling (hands, feet): vasodilation of peripheral vessels
cramps (electrolyte imbalance)
Systemic
increased core temperature, dehydration, syncope (drop in blood pressure)
Acute manifestation
heat stroke (inability to maintain heat balance at 0)
cardiac arrest

Number of deaths per day in Switzerland, heat wave summers 2003, 2015, 2018

Source: OFEV 2019



Effects of heat stress

Mortality among workers

- Healthy adults
- Unspecific symptoms
- Generally poorly reported
- Attracts attention during heat waves

Mortality in the general population

- Mostly vulnerable populations
- Sub-acute mechanisms
- Attracts attention during heat waves
- Moderate compared to cold-related mortality

Revealed: hundreds of migrant workers dying of heat stress in Qatar each year

As construction boom hits its peak ahead of Fifa World Cup, Guardian analysis shows workers toiling in potentially fatal temperatures

Dead at 24: did heat kill Doha World Cup worker Rupchandra Rumba?

A migrant worker at the construction site for the Al-Rayyan stadium, near Doha. Photograph: Tom Jenkins/The Guardian

Mechanisms of thermoregulation

Objective:

Maintain the body's core temperature (<38°)!

Hot environments

- Sweat regulation (evaporation of sweat)
- Vasodilatation of peripheral blood vessels

Acclimatization

- Physiological adaptation process (~10 days)
- Sweating: faster, more abundant, better distributed
- Lower core temperature
- Lower heart rate

Heat stress, evaluation

Measurement of a heat stress index combining the effects of convection, evaporation and radiation (WBGT Wet Bulb Globe Temp.)

without sunlight

$$WBGT = 0.3\,t_g + 0.7\,t_{nw}$$

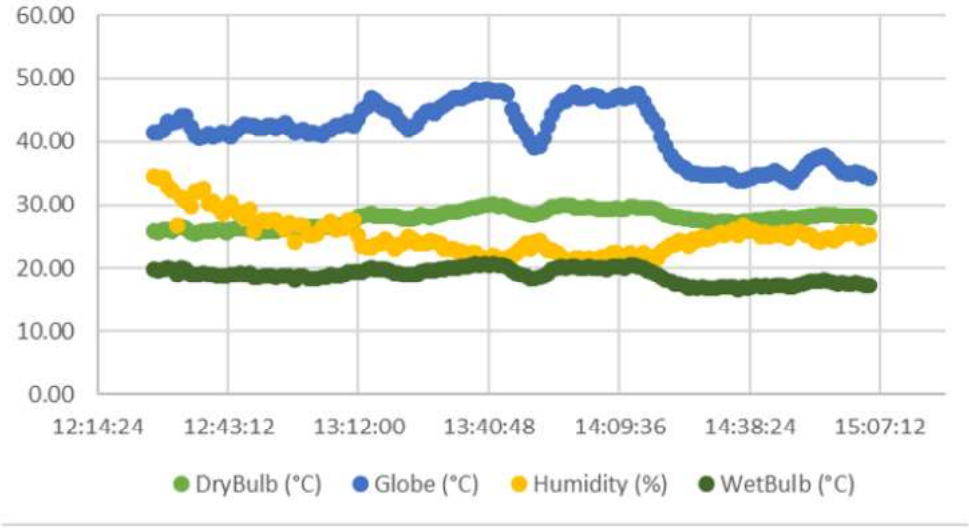
with sunlight

$$WBGT = 0.2\,t_g + 0.7\,t_{nw} + 0.1\,t_a$$

Tw: Wet temp., Tg: Global temp,
Ta: Air temp.

Heat stress, evaluation

WBGT Measurements in the buiding sector



Ambient temperature is not a good estimate of heat stress levels.

Heat stress, thresholds

Take into account acclimatization, physical activity and duration of exposure

Reference values of WBGT heat stress index from ISO 7243 related to a maximum rectal temperature of 38°C

	Metabolic rate, M		WBGT Reference value			
Metabolic Rate class	Related to a unit skin surface area W/m-2	Total (for a mean skin surface area of 1.8m2) W	Person acclimatised to heat °C		Person not acclimatised to heat °C	
0 (resting)	$M \leq 65$	$M \leq 117$	33		32	
1	$65 < M \leq 130$	$117 < M \leq 234$	30		29	
2	$130 < M \leq 200$	$234 < M \leq 360$	28		26	
3	$200 < M \leq 260$	$360 < M \leq 468$	No sensible air movement 25	Sensible Air movement 26	No sensible air movement 22	Sensible air movement 23
4	M>260	M>468	23	25	18	20

Source: Health and Safety Laboratory, UK

Heat stress, metabolic classes

Wide variation in energy production according to metabolism

Activity	Examples	Produced E [W]
Resting	Sitting at the desk	115
Low (1)	Drilling, milling	180
Moderate (2)	Walking, pneumatic hammer work	300
High (3)	Shovelling, hammering	415
Very high (4)	Climbing stairs, excavating at an intensive pace	520

Heat stress, thresholds

Recommended values in Switzerland

Requirements in terms of exposure time (% of activity, breaks, hydration...)

	Acclimatation				Sans acclimatation			
Type de travail	Léger	Moyen	Intense	Très intense	Léger	Moyen	Intense	Très intense
100% travail	29.5	27.5	26		27.5	25	22.5	
75% travail 25% repos	30.5	28.5	27.5		29	26.5	24.5	
50% travail 50% repos	31.5	29.5	28.5	27.5	30	28	26.5	25
25% travail 75% repos	32.5	31	30	29.5	31	29	28	26.5

Exposed workers

Extreme cold situations

- artificial sources: refrigeration plants, food, ice rinks
- environmental situations: extreme cold, altitude, wind

Mechanisms of thermoregulation, effects

Physiological mechanisms

- Vasoconstriction of skin vessels / heat conservation
- Shivering / endogenous heat production

Behavioral adaptations

- Dressing
- Increasing physical activity, endogenous heat production

Effects

- Frostbite
- Hypothermia
- Loss of manual dexterity / increase in reaction time (effect on performance)

Cold stress, thresholds

Takes into account wind speed (convection)
Exposure time requirements

Wind Chill Index (WCI), equivalent temperature Tch

WIND CHILL CHART

		Ambient Temperature (∞C)								
		4	-1	-7	-12	-18	-23	-29	-34	-40
Wind km/h	**Velocity mph**	**Equivalent Chill Temperature (∞C)**								
Calm										
0	0	4	-1	-7	-12	-18	-23	-29	-34	-40
8	5	3	-3	-9	-14	-21	-26	-32	-38	-44
16	10	-2	-9	-16	-23	-30	-35	-43	-50	-57
24	15	-6	-13	-20	-28	-36	-43	-50	-58	-65
32	20	-8	-16	-23	-32	-39	-47	-55	-63	-71
40	25	-9	-18	-26	-34	-42	-51	-59	-67	-76
48	30	-16	-19	-22	-36	-44	-53	-62	-70	-78
56	35	-11	-20	-29	-37	-46	-55	-63	-72	-81
64	40	-12	-21	-29	-38	-47	-56	-65	-73	-82

Adapted from: Threshold Limit Values (TLV™) and Biological Exposure Indeces (BEI™) booklet; published by ACGIH, Cincinnati, Ohio

Little danger in less than one hour exposure of dry skin

DANGER – Exposed flesh freezes within one minute

GREAT DANGER – Flesh may freeze within 30 seconds

Maximum danger of false sense of security

Example

Installation of rebar

Work at altitude (~2000m), 1/2 day
Evaluation approach

- measurement of the thermal environment
- calculation of Chill Temperature
- estimation of metabolic activity
- estimation of the required protection

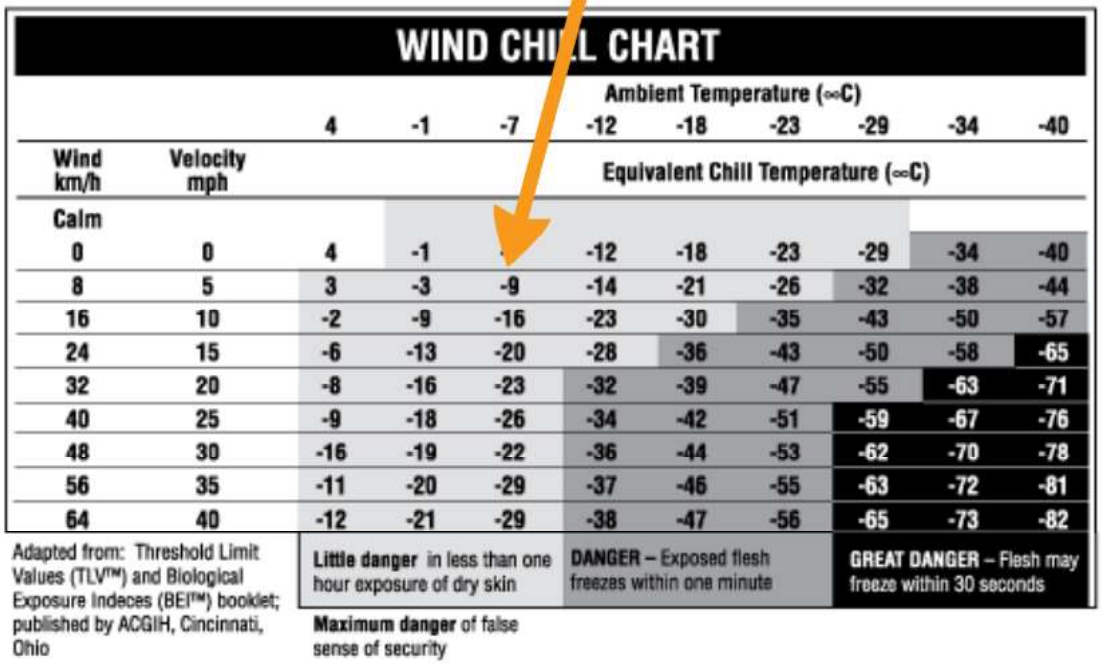
Source SECO

Example

Thermal environment

Air temperature : -5 °C
Wind speed: 4 m/s (flag raised)

Corresponding Chill temperature



WIND CHILL CHART

Wind Velocity	Ambient Temperature (∞C)								
	4	-1	-7	-12	-18	-23	-29	-34	-40
km/h mph	Equivalent Chill Temperature (∞C)								
Calm									
0 0	4	-1	[illegible]	-12	-18	-23	-29	-34	-40
8 5	3	-3	-9	-14	-21	-26	-32	-38	-44
16 10	-2	-9	-16	-23	-30	-35	-43	-50	-57
24 15	-6	-13	-20	-28	-36	-43	-50	-58	-65
32 20	-8	-16	-23	-32	-39	-47	-55	-63	-71
40 25	-9	-18	-26	-34	-42	-51	-59	-67	-76
48 30	-16	-19	-22	-36	-44	-53	-62	-70	-78
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Maximum danger of false sense of security

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Metabolic activity

Moderate

Example

Required protection

Protective clothing required defined on the basis of
Metabolic activity and Chill temperature

Other preventive measures

- heated break room
- hot beverages
- exposure duration

Vulnerable groups

- pregnant women
- cold-induced asthma
- people:
- over 55 years of age
- weakened in their health: cardiovascular diseases, diabetes, hypertension, ...
- suffering from white finger disease (Raynaud's syndrome)...

Thermal comfort

Optimal conditions of temperature, humidity and air flow

T: 19-21° C
H; >20%
air: < 0.25 m/s

High inter-individual variability

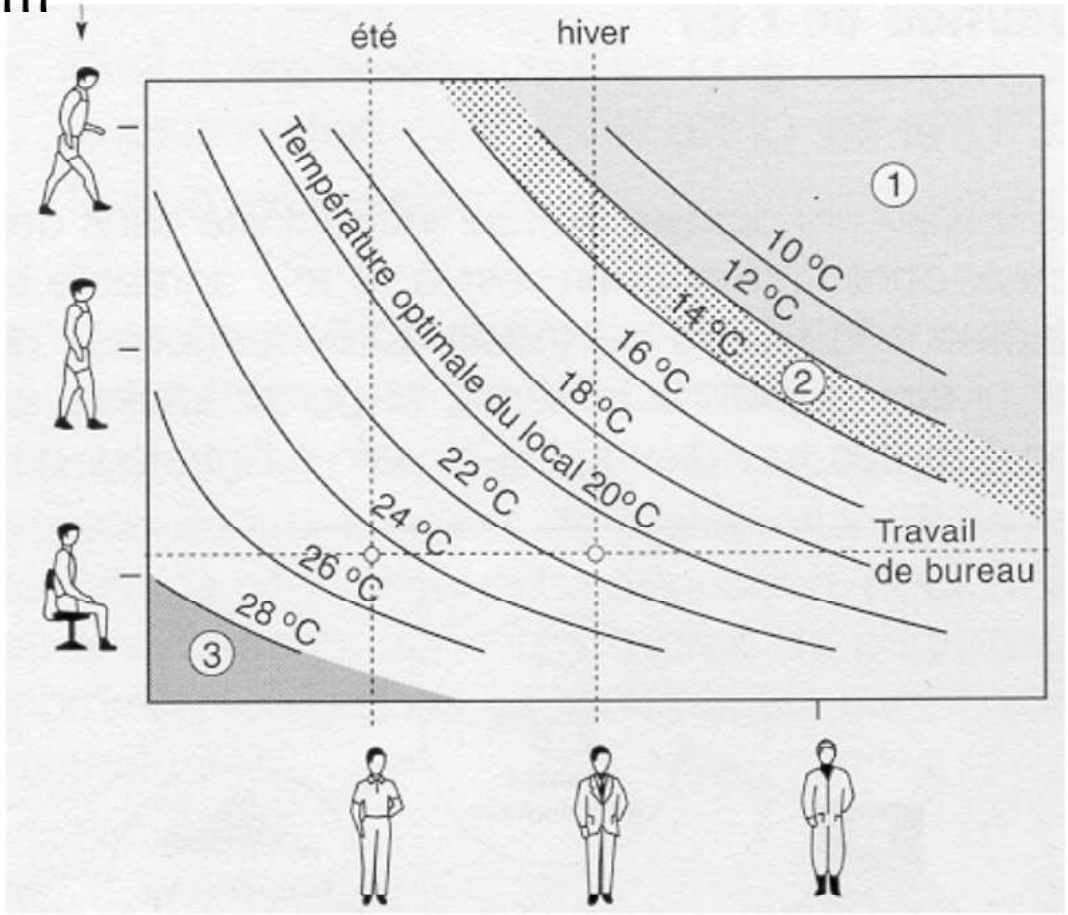
Thermal comfort, evaluation

Criteria

- balanced thermal equilibrium
- sweat evaporation
- skin temperature
- absence of discomfort

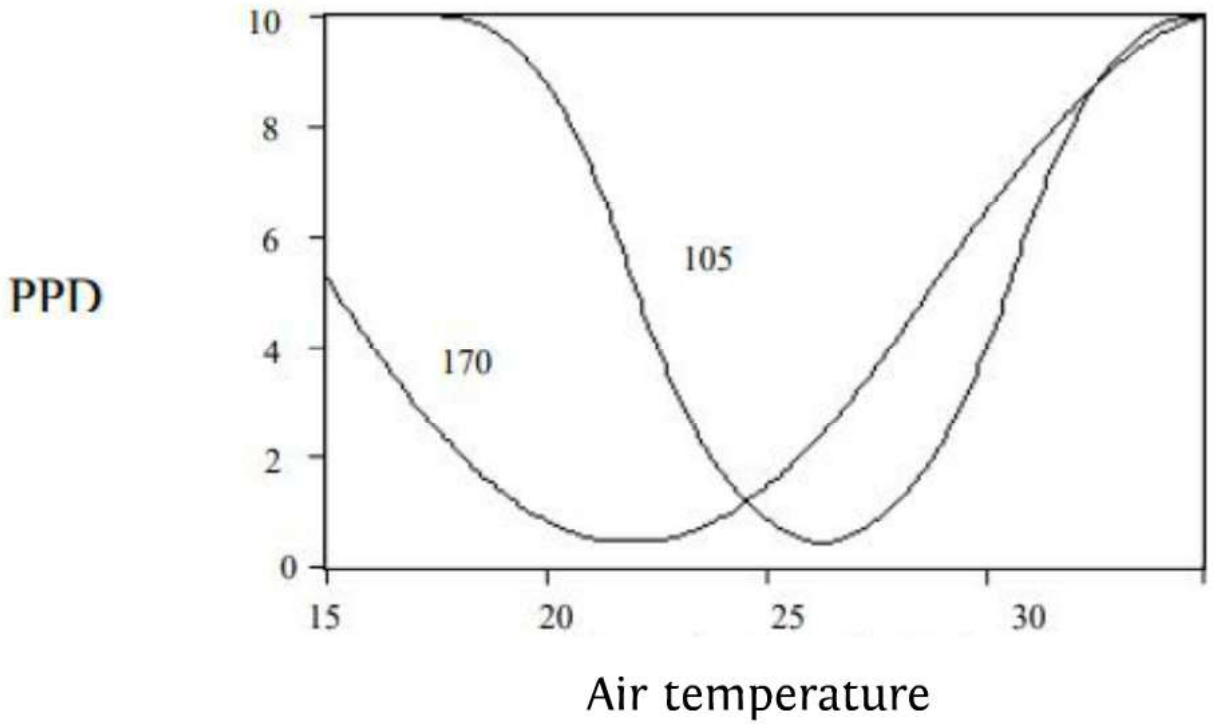
PMV (Predicted Mean Vote)comfort

- criteria based on voting (>1000 pers.)



Thermal comfort, evaluation

Comfort criteria based on the number of dissatisfied
PPD (Predicted Percentage of Dissatisfied)
seated rest (105W), light work (170W)



Confounding factors
Job dissatisfaction thermal dissatisfaction increased by 50%.