Predicted Heat Strain index (PHS) MODEL

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ISO 7933 " interpretation of thermal stress using the Required Sweat Rate"

Main criticisms concerned:

- The prediction of the skin temperature
- The influence of the clothing on convection, radiation and evaporation
- The increase of core temperature linked to the activity
- The prediction of the sweat rate in very humid conditions
- The limiting criteria and in particular the "alarm" and "danger" level
- The maximum water loss allowed.

Predicted skin temperature

Material and Methods

- HEAT database (1113 files) containing minute by minute values of 10 parameters of stress and strain
- only data from male subjects
- Final TSK database includes 1999 data points coming from 1399 conditions with 377 male subjects

Ranges of validity of the PHS model		
	Min	Max
t_a °C	15	50
P_a kPa	0	4.5
t_r-t_a °C	0	60
v_a m/s	0	3
M W	100	450
I_{cl} clo	0.1	1.0

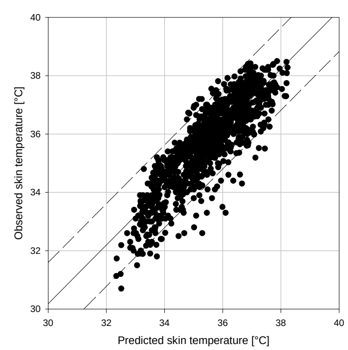
Predicted skin temperature

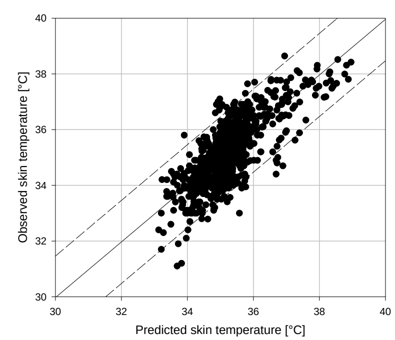
Prediction model: nude subjects

$$t_{sk} = 7.19 + 0.064\ t_a + 0.061\ t_r + 0.198\ p_a - 0.348\ v_a + 0.616\ t_{re}$$

clothed subjects

$$t_{sk} = 12.17+0.020\ t_a+0.044\ t_r+0.194\ p_a - 0.253\ v_a+0.003\ M+0.513\ t_{re}$$





Prediction of t_{re} from the core temperature

- The core temperature t_{co} is the mean of
  - the rectal temperature: characteristic of the muscle mass
  - the oesophageal temperature: characteristic of the blood and influencing the hypothalamus.

Edwards et al.: $t_{oe} = a\, t_{re} + b \frac{dt_{re}}{dt} + c$

$$t_{re} = t_{re0} + \frac{2\, t_{co} - 1.962\, t_{re0} - 1.31}{9}$$

Increase in t_{co} associated with M

Saltin (1966), in a neutral condition,

- t_{cor} = 0.002M + 36.6 (M in watts)
- t_{co} reaches t_{cor} with a time constant of about 10 minutes.

⇒ $t_{co} = t_{co0} \cdot k + t_{cor} \cdot (1-k)$

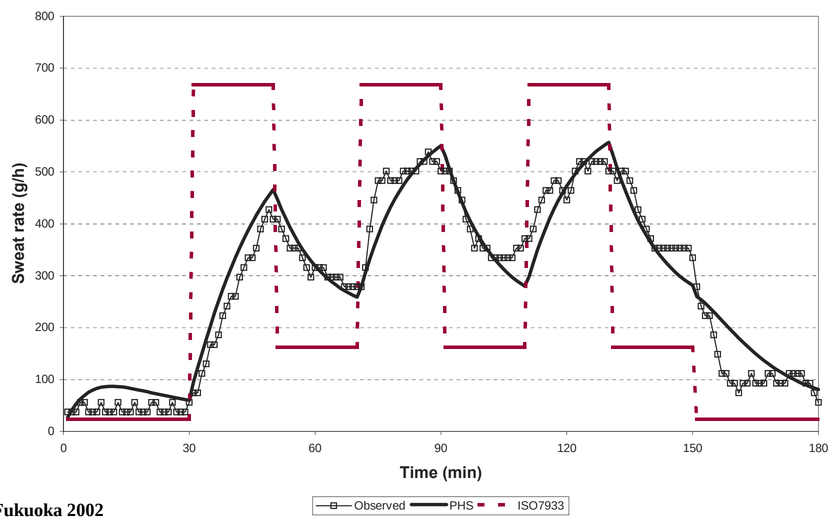
where: k = exp(-incr/10)
incr = the time increment, in minutes.
t_{co} = core temperature at time i
t_{co0} = core temperature at time (i-1)

⇒ Heat storage associated with this increase:

$$dS_R = c_{sp}\, (t_{co} - t_{co0})\, (1 - \alpha)$$

Exponential averaging for t_{sk} , SW

Observed and predicted SW (using ISO 7933 and PHS) in a lab experiment with 3 sequences of work and climate.



Maximum sweat rate: SW_{max}

ISO 7933 assumes constant values of maximum sweat rate for acclimatised and unacclimatised subjects

- Araki et al. (1979):

⇒ SW_{max} = 2.6 (M - 58) g/h

- for M < 300 watts : 650 g/h
- limited to 1000 g/h for unacclimatised subjects

⇒ SW_{max} = M - 58 W/m² in the range from 250 and 400 W/m²

For acclimatised subjects:

- sweating in a given environment greater by a factor 2
- MAXIMUM sweat rate increase by 25% (Havenith 1997)

Maximum dehydration and water loss

Szlyck (1989): threshold for thirst: 2% loss of body weight
Candas et al. (1985): at 3% dehydration:

- hypertonic hypovolemia
- increased heart rate
- depressed sweating sensitivity.

⇒ **maximum dehydration in industry (not army or sports): 3% of body mas**

Kampmann et al.(1995): with exposure 4 to 8 hour

- average rehydration rate of 60%
- rehydration rate greater than 40% for 95% of the subjects

⇒ **Maximum water loss**

- 7.5% of the body mass for an average subject
- 5% of the body mass for 95% of the working population

Limit of internal temperature

WHO document 1969:

- *Limit of 38°C commonly adopted and implicitly adopted in ISO 7933*

Maximum rectal temperatures:

- 42° the maximum internal temperature to avoid any physiological sequels
- 39.2° "may rapidly lead to total disability in most men with excessive, often disturbing, physiological changes" Wyndham et al. (1965).

Maximum probabilities:

- for 42°: < 10^{-6} : <one heat stroke every 4 years among 1000 workers (250 days/year)
- for 39.2°: < 10^{-3} : <1 person at risk among 1000 shifts.

Limit of internal temperature

Wyndham's data

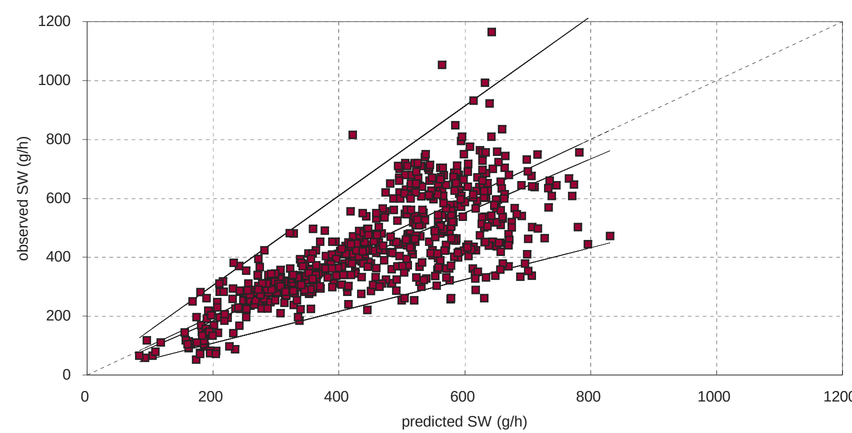
- for non acclimatised workers
  - 38.7°C for $p \leq 10^{-6}$ of reaching 42°C
  - 38.2°C for $p \leq 10^{-3}$ of reaching 39.2°C
- for acclimatised workers
  - 39.4°C for $p \leq 10^{-6}$ of reaching 42°C
  - 38.3°C for $p \leq 10^{-3}$ of reaching 39.2°C

Clearly, the 38.7 and 39.4°C are not defendable 38.3° and 38.2° are closed to 38°C (WHO document)

⇒ **limit at 38°C**

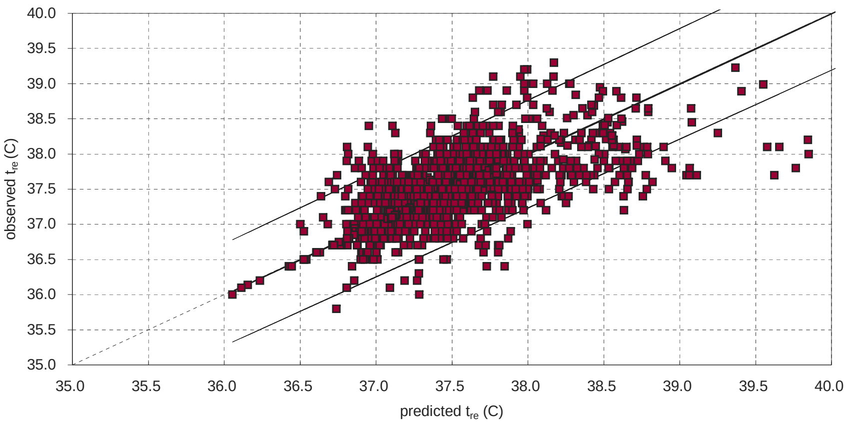
Validation in laboratory experiments: SW

Observed and predicted sweat rates (95% confidence interval): 672 laboratory experiments



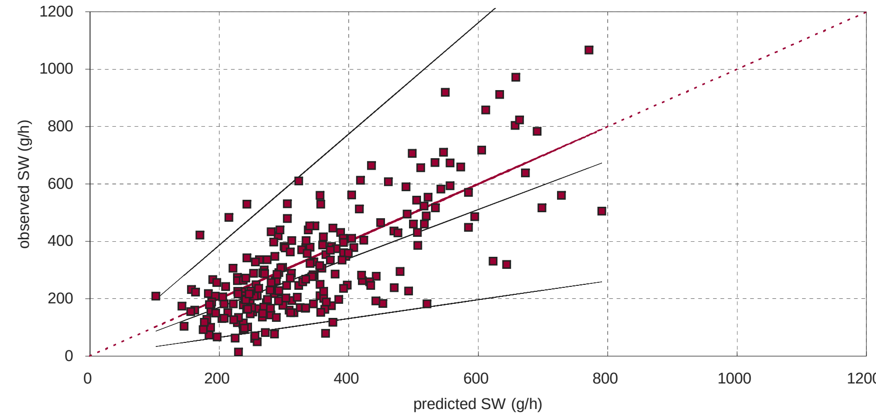
Validation in laboratory experiments: t_{re}

Observed and predicted rectal temperature (95% confidence interval): 672 laboratory experiments



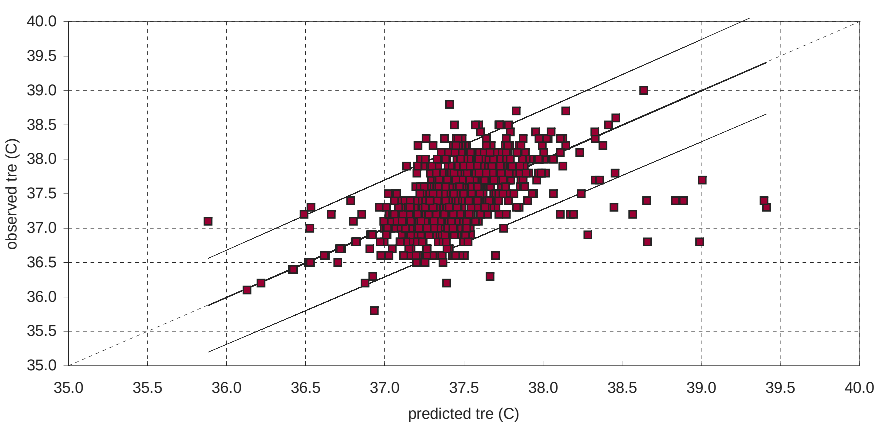
Validation in field experiments: SW

Observed and predicted sweat rates (95% confidence interval): 237 field experiments

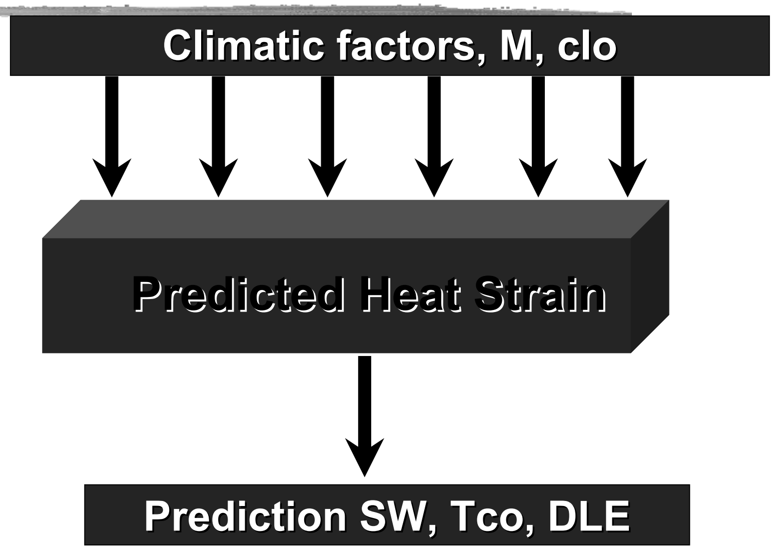


Validation in field experiments: t_{re}

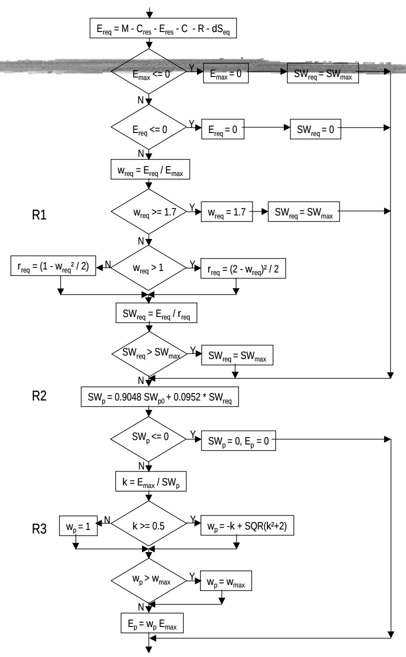
Observed and predicted rectal temperature (95% confidence interval): 237 field experiments

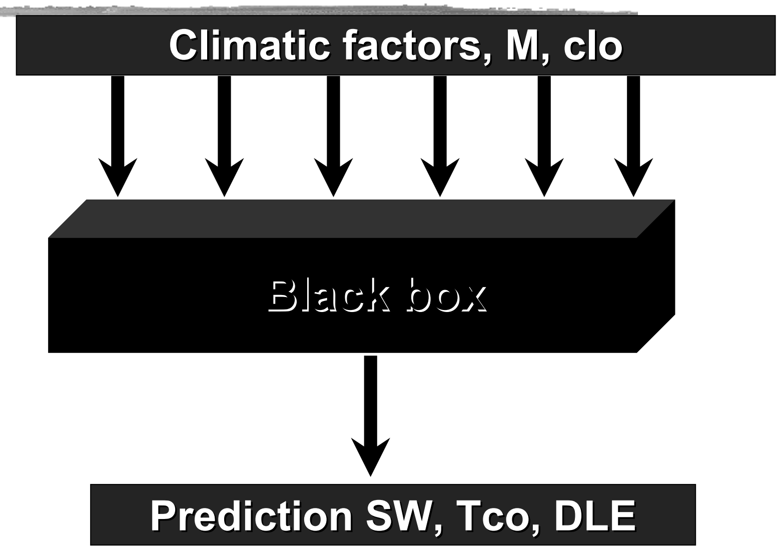


Strategy for the management of the thermal working conditions

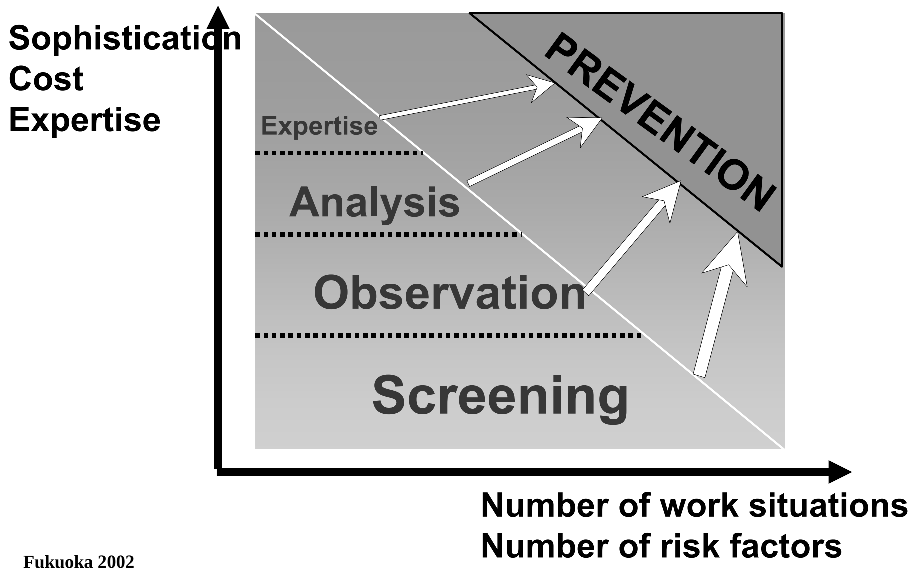


Symbol	Term	Unit	Symbol in the program
-	code =1 if walking speed entered, 0 otherwise	-	defspeed
-	code =1 if walking direction entered, 0 otherwise	-	defdir
α	fraction of the body mass at the skin temperature	dimensionless	-
α_i	skin-core weighting at time i	dimensionless	TskTcrwg
α_{i-1}	skin-core weighting at time (i-1)	dimensionless	TskTcrwg0
ε	emissivity of the bare skin	dimensionless	-
τ	time constant	min	-
θ	angle between walking direction and wind direction	degrees	Theta
A_{Du}	Dubois body surface area	square metre	Adu
A_p	fraction of the body surface covered by the clothing	dimensionless	Ap
A_r	effective radiating area of the body	dimensionless	Ardu
C	heat flow by convection at the skin surface	Watts per square metre	Conv
c_e	water latent heat of evaporation	Joules per kilogram	-
$C_{orr,cl}$	correction for the dynamic clothing insulation for totally clothed subjects	dimensionless	CORcl
$C_{orr,Ia}$	correction for the dynamic boundary layer insulation	dimensionless	CORia
$C_{orr,tot}$	correction for the dynamic clothing insulation as a function of the actual clothing	dimensionless	CORtot
$C_{orr\,E}$	correction for the dynamic permeation rate	dimensionless	CORe
c_p	specific heat of dry air at constant pressure	Joules per kilogram of dry air	-
C_{res}	heat flow by respiratory convection	Watts per square metre	Cres
c_{sp}	specific heat of the body	Watts per square meter per degree celsius	spHeat
D_{lim}	allowable exposure duration	min	Dlim
$D_{lim\,tre}$	allowable exposure duration for heat storage	min	Dlimtre
$D_{limloss50}$	allowable exposure duration for water loss, mean subject	min	Dlimloss50
$D_{limloss95}$	allowable exposure duration for water loss, 95% of the working population	min	Dlimloss95
D_{max}	maximum water loss	grams	Dmax
D_{max50}	maximum water loss to protect a mean subject	grams	Dmax50
D_{max95}	maximum water loss to protect 95% of the working population	grams	Dmax95
dS_i	heat stored during the last time increment	Watts per square metre	dStorage
dS_{eq}	body heat storage rate for increase of core temperature associated with the metabolic rate	Watts per square meter	dStoreq





Prevention Strategy



	Stage 1 *"Screening"*	Stage 2 *"Observation"*	Stage 3 *"Analysis"*	Stage 4 *"Expertise"*
• When?	Systematically	When a "problem" is detected	More complicated Cases	Very complex cases
• How?	Opinions	Qualitative observations	Ordinary measurements	Specialised measurements
• Cost?	Very low	Low	Average	High
• Duration (order of magnitude)	10 min	2 hours	1 day	A few days
• By whom?	Workers + company management	Workers + company management	Same + specialists	Same + specialists + experts
• Knowledge - working conditions - ergonomics	Very high Low	High Average	Average High	Low Specialised

Stage 2 : OBSERVATION

Observation designed to:

- Identify particular circumstances, specific tasks, unusual working conditions where a "problem" exists
- Determine what to do to reduce or eliminate these problems: straightforward solutions
- By or with the help of the workers themselves.

Conclusion:

- Is the "problem" satisfactorily controlled or not?
- If not, the assistance of specialists is needed.

Criteria for OBSERVATION

Designed for the workers and their management

- Simple to understand by untrained people
- Avoid concepts or terms not readily understood
- Easy to use, maximum 1 hour for a specific work situation
- Based on simple *OBSERVATIONS* (no measurement)
- Oriented towards prevention

Stage 2: OBSERVATION

1. Describe the working condition known to or likely to raise a thermal problem
2. Evaluate the situation for each of the six parameters separately on scales of discomfort
3. Determine the immediate possible solutions
4. Determine what the situation might be afterwards
5. Determine globally how acceptable the situation is
6. Determine whether a stage 3, *Analysis* is necessary

Temperature scale

AIR TEMPERATURE	
-3	• Generally freezing
-2	• Generally between 0 and 10°C.
-1	• Generally between 10 and 18°C
0	• Generally between 18 and 25°C
1	• Generally between 25 and 32°C
2	• Generally between 32 and 40°C
3	• Generally greater than 40°C

Temperature: solutions

AIR TEMPERATURE

- Locate the sources of heat or cold in the periphery
- Eliminate the sources of hot or cold air
- Insulate the hot surfaces
- Exhaust hot or cold air locally
- Ventilate without draughts
- Use clothes with lower or higher insulation
- ...

Humidity and radiation scale

HUMIDITY	
-1	- Dry throat/eyes after 2-3 hours
0	- Normal
1	- Moist skin
2	- Skin completely wet
THERMAL RADIATION	
-1	- Cold on the face after 2-3 minutes
0	- No radiation discernible
1	- Warm on the face after 2-3 minutes
2	- Unbearable on the face after > 2 minutes
3	- Immediate burning sensation

Humidity and radiation: solutions

HUMIDITY

- Eliminate the leaks of vapour and water
- Enclose all evaporating surface
- Use clothes waterproof but permeable to vapour
- …

THERMAL RADIATION

- Reduce the radiating surfaces
- Use reflecting screens
- Insulate or treat the radiating surface
- Locate workstations away from radiating surfaces
- Use special protective clothes reflecting radiation
- …

Air movement and work load scales

AIR MOVEMENTS	
-2	. cold strong air movements
-1	. cold light air movements
0	. no air movements
1	. warm light air movements
2	. warm strong air movements
WORK LOAD	
0	. office work: easy low muscular constraints,
1	occasional movements at normal speed.
2	. Moderate work with arms or legs
	. Intense work with arms and trunk
3	. very intense work at high speed: stairs, ladders

Air movement and work load: solutions

AIR MOVEMENTS

Reduce or eliminate air draughts
Use screens to protect locally against draughts
Locate workstations away from air draughts
…

WORK LOAD

Reduce the movements during work
Reduce displacements
Reduce the speed of movements
Reduce the efforts, use mechanical assistance…
Improve the postures…

Clothing and opinion scales

CLOTHING		
0	-	light, flexible, not interfering with the work
1	-	long, heavier, interfering slightly with the work
2	-	clumsy, heavy, special for radiation, humidity
3	-	special overalls with gloves, hoods, shoes
OPINION OF THE WORKERS		
-3	-	shivering, strong discomfort for the whole body
-2	-	strong local discomfort overall sensation coolness
-1	-	slight local cool discomfort
0	-	no discomfort
1	-	slight sweating and discomfort thirst
2	-	heavy sweating, work pace modified
3	-	excessive sweating, special clothing

Clothing solutions

CLOTHING

- Improve the design of the clothing
- Select more suitable materials
- Look for lighter materials
- ...

Synthesis of the results for the present situation

	-3	-2	-1	0	1	2	3
Air temperature							O
Humidity						O	
Radiation					O		
Air movements				O			
Work Load						O	
Clothing							O

Synthesis of the results for the future situation

	-3	-2	-1	0	1	2	3
Air temperature						X	O
Humidity					X	O	
Radiation					=		
Air movements				=			
Work Load					X	O	
Clothing					X		O

Stage 2: *Observation*

- Measures to be taken in the short-term:
  - Hot or cold drinks
  - Recovery periods
  - Work organisation
  - Clothing....
- Decide whether a more detailed *Analysis* is needed to quantify and to solve the problem.

Stage 3: *Analysis*

Stage 3: *Analysis*

- **Deal with specific conditions**
- **Usually involve measurements**
- **Conducted with the help of OH services with adequate training**
  - **To find technical solutions**
  - **To define organisational solutions**
  - **and short-term protection measures**
- **Use common concepts and techniques and, if necessary, simple measurements**
  - **to identify the causes of the problems**
  - **and the means to solve them**
- **Useable in less than one day**
- **Oriented towards prevention**

Analysis: Procedure

- **Analyse the sequence of activities:**
  - **Description of the activities.**
  - **Mean and maximum durations.**
  - **Period concerned by the working situation.**
  - **Exposed workers**

during representative period(s) of time

  - **Measurement or estimation of the mean and maximum values**
  - **Computation of the indices PMV-PPD, PHS**

Analysis : Synthesis

	Activity ...		Activity ...	
	mean	Max	mean	max
t_a RH t_g v_a M Clo				
PMV PPD WBGT PHS / DLE				

Analysis : interpretation

Risk in the present situation

cold constraint	PMV < -2
cold discomfort	-2 < PMV < -0,5
comfort	-0,5 < PMV < 0,5
warm discomfort	0,5 < PMV < 2
constraint in the long term	DLE < 480 min
constraint in the short term	DLE < 120 min
immediate constraint	DLE < 30 min

Analysis: Procedure

- Determine the acceptability of the working condition by comparing:
  - mean-maximum duration of each activity
  - the DLEs.
- Define prevention - control techniques
- Define the optimum work organisation.
- Determine the residual risk after implementation of these prevention/control measures.

Analysis : synthesis

	Activity ...	Activity

3. RISK
• Class of risk
• If heat stress
  • Sweating rate
  • Water loss per day
  • DLE		

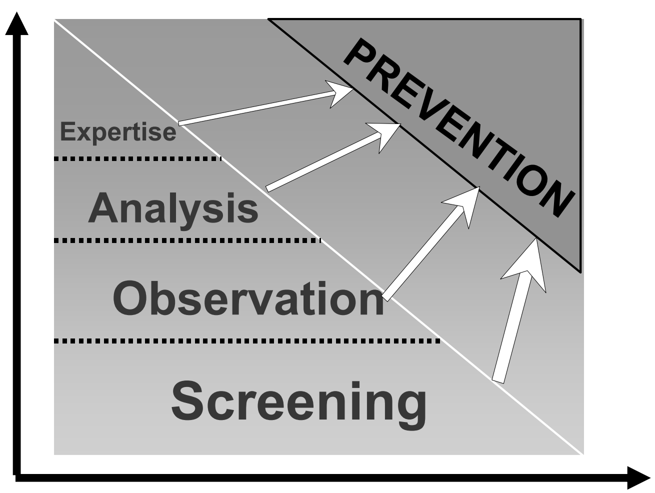
4. ACCEPTABILITY		
5. PREVENTION/CONTROL MEASURES		
6. RESIDUAL RISK		
7. NEED FOR AN EXPERTISE		
8. SHORT TERM MEASURES		
9. MEDICAL SURVEILLANCE		

Stage 4: *Expertise*

Stage 4: Expertise

- Better characterise some heat or cold sources and/or some unusual circumstances
  - Specific measurements
  - Specific investigation techniques
- Characterise the overall exposure of the workers
- Look for sophisticated prevention/control measures

Prevention Strategy



Thank you