

# Occupational Heat Stress Assessment by the Predicted Heat Strain Model

J.B.M. MALCHAIRE

Occupational Hygiene and work Physiology, Catholic University of Louvain, Clos Chapelle aux Champs, 3038, B-1200 Brussels, Belgium

*Received January 16, 2006 and accepted April 12, 2006*

**Abstract:** The work of the main European research teams in the field of thermal factors was coordinated in order to improve significantly the Required Sweat Rate model published as an international standard. Many significant modifications were brought, in particular concerning the effects of forced convection, body movements and exercise and the prediction of the skin temperature as a function of the rectal temperature and in case of severe conditions of radiation, humidity and clothing. The criteria for acceptable work durations in hot environments were updated concerning the maximum increase in core temperature and the acceptable water loss. The revised model, called Predicted Heat Strain model, was validated through a set of lab and field experiments involving stable and fluctuating conditions with high and low radiation, humidity and air velocity. It is meanwhile adopted as an ISO and CEN standard. In addition, a strategy was developed to assess the risks of heat disorders in any working situation. It is based on the three highest stages of the SOBANE strategy: an “Observation” method for improving simply the thermal conditions of work; an “Analysis” method to evaluate the magnitude of the problem and optimise the choice of solutions and an “Expert” method for in depth analysis of the working situation when needed.

**Key words:** Heat stress, Prevention, Strategy, Heat indices, ISO 7933

## Introduction

The objective of the research project was to coordinate the work of the some of the main European research teams in the field of thermal factors in order to develop and improve significantly the available methods to evaluate the risk of thermal strain during work in hot environments.

The standard ISO 7933<sup>1)</sup> “Analytical Determination and Interpretation of the Thermal Stress based on the calculation of Required Sweat Rate” was published for the first time in 1989. Since, it was abundantly criticized and many papers were published comparing a version (not always indicated) of the required Sweat Rate index with sets of data.

Although such comparisons were each time limited to a particular set of data, systematic criticisms concerned:

- The prediction of the skin temperature
- The influence of clothing on convection, radiation and evaporation

- The combined effect of clothing and movements
- The increase in core temperature related to activity
- The exposure limit criteria and in particular the alarms and danger levels
- The allowed maximum water loss.

The points requiring a concerted research were consequently identified as being:

- The coefficients of heat exchange by convection, radiation and evaporation in extreme conditions.
- The modelling of the physiological behaviour during work to heat and, in particular, of the average skin temperature, the core temperature (rectal) and sweat rate.
- The criteria for the determination of the exposure duration limit, taking account of the interindividual differences between the workers.

The specific objectives of the research project consequently were:

- To extend the validity of the previous Required Sweat Rate model by better taking account of clothing.
- To improve the validity of the model in the event of high radiation, high moisture or high air velocity.
- To better define the criteria for the determination of the exposure duration limits and in particular the interindividual differences in term of sweat rate, evaporative efficiency, water loss and increase in core temperature.

With all the experience that the participants to the research had in the field concerning the improvement of the climatic conditions of work, the group reached the conclusion that ISO standard 7933, describing the Required Sweat Rate was so sophisticated that it was simply not understood nor used in industry. This situation was likely to be worse as the complexity increased for the Predicted Heat Strain.

It was realized that the WBGT index, in spite of its lack of validity, was the main tool to describe a hot environment of work, due mainly to its simplicity and the fact that it is expressed in terms of a temperature. It is clear that this simplicity is more apparent than real (what is the rationale in the organization of the recommended work–rest regimens?) and is sometimes source of confusion (how to explain to people in the field that the WBGT is 25°C, while the local thermometer indicates 36°C?).

Nevertheless, an attempt was made to derive an index expressed also in terms of an “equivalent” temperature. It failed, proving at the same time the lack of validity of the WBGT index.

Another attempt concerned the use of the PHS index and the strategy to improve working conditions in the heat. Since the mathematics of the PHS model is too difficult to understand, it should simply not be explained to potential users in the field and should be used as a black box, providing estimates of the core temperature and the sweat rate when the conditions of exposure are introduced: indeed, no one needs to understand how works an engine in order to drive a car.

The specific objective of this part of the research project consequently was to conceive and validate a strategy of evaluation of the constraint during work in hot environments, strategy likely to be used by people in the field to determine the exposure duration limits and to optimize the improvement of the work environment.

### **Influence of Clothing on the Heat Transfers by Convection and Evaporation**

The heat loss by convection is a main part of the heat

loss of the human body, particularly in moderate climates.

In hotter environments, the heat loss depends more on evaporation, itself function of the characteristics of clothing.

An important aspect of the transfers of heat per convection and evaporation is the effect wind velocity and movements on the transfer coefficients on the surface layer of the clothes.

The tables of standard ISO 9920<sup>2)</sup> give static values of heat insulation for various clothing sets. A factor played by clothing in the heat transfer is that it increases the heat transfer surface between the body and the environment. This increase is larger as the clothing is thicker and more insulating.

The research was mainly concerned with the combined effect of the movement and wind on clothing. Starting from experiments with subjects and on mannequins, the study made it possible to develop various expressions of correction<sup>3-5)</sup>, according to the wind velocity, the direction and the velocity of walk and the workload. Simple expressions were developed to correspond to more common working conditions.

### **Prediction of the Skin Temperature ( $t_{sk}$ )**

A common structure was defined to gather in the same data base, all the data coming from 1,113 experiments carried out by the various partners. For each experiment, the minute per minute values of 10 constraint parameters were available, among which the observed skin temperature, calculated as a weighted average of at least 4 local measurements. Points corresponding to constant conditions were selected in each experiment.

Few data (less than 10%) being available for women, it was decided to use in the model the prediction of  $t_{sk}$  on the basis of data only relating to men. Consequently, the final data base included 1999 points of data concerning 377 subjects.

The analysis was carried out separately for naked subjects (1,212 points with less than 0.2 clo) and clothed subjects (787 points between 0.6 and 1 clo).

The relation between the average  $t_{sk}$ , the primary climatic parameters, the metabolic rate and the rectal temperature was represented by an additive model.

For the subset of data relating to the *naked subjects*, a model of prediction excluding the non significant variable metabolic rate was obtained:

$$t_{sk} = 7,19 + 0,064 t_a + 0,061 t_r + 0,198 P_a - 0,348 v_a + 0,616 t_{re}$$

with  $t_a$  = the air temperature (°C)

$t_r$  = the mean radiant temperature (°C)

$P_a$  = the partial water vapour pressure (kPa)

$v_a$  = the air velocity ( $\text{ms}^{-1}$ )

$t_{re}$  = the rectal temperature ( $^{\circ}\text{C}$ )

The multiple coefficient of correlation between the observed values and predicted was equal to 0.86 and 83,3% of the predicted skin temperatures were in the range of  $\pm 1^{\circ}\text{C}$  from the observed values.

The following model was obtained for the *clothed subjects*

$$t_{sk} = 12,17 + 0.020 t_a + 0.044 t_r + 0.194 P_a - 0.253 v_a + 0.00297 M + 0.513 t_{re}$$

with  $M$  = the metabolic rate ( $\text{Wm}^{-2}$ )

The coefficient of correlation (0.77) was lower than for naked subjects, but 81.8% of the predicted values were in the range of  $\pm 1^{\circ}\text{C}$  from the observed values.

An article showing the detail of these new models was published<sup>6)</sup>.

### **The Model of Prediction of the Thermal Strain (PHS: Predicted Heat Strain)**

#### *Respiratory heat losses by evaporation and convection*

Although these losses are relatively limited during work in hot environments, they are often of the same order of magnitude as the convection heat loss. However, the storage of heat is determined by the difference between the required and predicted evaporation rates. In very hot environments, respiratory losses can consequently come to play a significant part in the thermal balance of the body. The former expressions were re-examined and improved on basis of work by Livingstone *et al.*<sup>7)</sup> (1994) and Varene<sup>8)</sup>, so as to hold account at the same time of ambient temperatures and moistures.

#### *The average body temperature*

From articles published by Kähkönen<sup>9)</sup> and Colin *et al.*<sup>10)</sup>, an algorithm was developed to predict the average body temperature by a weighted average of the temperatures rectal and skin. The weight allotted to the latter varies from 30% when the rectal temperature is  $36.8^{\circ}\text{C}$  with 10% only when it is equal to  $39^{\circ}\text{C}$ . This algorithm thus takes into account the peripheral vasodilatation associated with a rise in core temperature.

#### *Distribution of the heat accumulated in the body*

An algorithm was developed to predict the distribution of heat between the skin layer and in the core of the body. Whereas the core temperature is taken constant, the

temperature is supposed to vary linearly between the skin surface temperature and the rectal temperature, through the thickness of the skin layer.

#### *Prediction of the rectal temperature*

On the basis of work of Edwards *et al.*<sup>11)</sup>, an algorithm was developed to predict the increase in the rectal temperature resulting from storage of heat.

#### *Exponential weighting for the skin temperature ( $t_{sk}$ ) and sweat rate (SW)*

As shown by Malchaire<sup>12)</sup>, the skin temperature and sweat rate at a certain time can be calculated by a recurrent exponential model according to the values existing at the previous moment and of the steady state towards which would evolve these parameters if the current thermal conditions were to exist indefinitely.

This exponential weighting makes it possible to predict the thermal state at any minute, in any variable climate, according to the conditions to which the person is exposed at that minute and what she was exposed during the minutes and hours that preceded.

#### *Possible maximum sweat rate*

Publications by Araki *et al.*<sup>13)</sup> and Gosselin<sup>14)</sup> suggested that the maximum sweat rate for an average non acclimatized subject can vary between 650 and 1,000 g/h, according to the metabolic rate.

For the acclimatized subjects, it is known that the sweat rate in a given environment can be twice greater than for a non acclimatized subject. However, this refers to the actual sweat rate and not to the maximum sweat rate capacity. By excluding the studies for which the maximum capacity was not reached, the review of the literature made it possible to conclude that the maximum sweat rate increases by only 25% on average for the acclimatized subjects<sup>15)</sup>.

#### *Increase in core temperature $t_{co}$ related to the metabolic rate $M$*

According to Saltin and Hermansen<sup>16)</sup>, in a neutral condition, the equilibrium core temperature  $t_{cor}$  corresponding to a metabolic rate  $M$  can be estimated by:  $t_{cor} = 36,6 + M / 500$  ( $M$  expressed in Watts).

The core temperature reaches this equilibrium temperature  $t_{cor}$  with a time constant of approximately 10 min.

It can be supposed that the body does not try to lose the heat stored during this adaptation and thus does not perspire for this purpose. Consequently, the required sweat rate must not be estimated from the required evaporation rate  $E_{req}$ , but

from the difference ( $E_{\text{req}} - \text{dSR}$ ), where dSR is the heat accumulated at a given time to reach this equilibrium temperature.

#### *Limit of the internal temperature*

Report 412 of WHO published in 1969<sup>17)</sup> mentioned that “it is not recommended that the body core temperature exceeds 38°C for a daily exposure to heavy work...”. Since then, this value of 38°C was regarded as the maximum value for which the probability of a heat disorder is negligible.

From work undertaken by Wyndham *et al.*<sup>18)</sup>, two maximum rectal temperatures could be proposed:

- 39.2°C: this could quickly lead to total disability in most men, with excessive, often disturbing, physiological changes.
- 42°C: the maximum rectal temperature to avoid any physiological sequels.

The probability to reach these temperatures could be limited as follows:

- for 39.2°C: less than  $10^{-3}$  (less than 1 person at risk among 1,000 shifts).
- for 42°C: less than  $10^{-6}$  (less than 1 severe heat stroke every 4 years among 1,000 workers) (250 d/yr)

From the data of Wyndham and Heyns<sup>19)</sup> and Kampmann<sup>20)</sup>, it was determined that the average rectal temperature had indeed to be limited to 38°C, as suggested by the WHO document, in order to respect these low probabilities.

#### *Dehydration and maximum water loss*

Candas *et al.*<sup>21)</sup> reported that a dehydration of 3% of the body mass increases the heart rate and decreases the sensitivity of sweating. This 3% value can consequently be accepted as the maximum allowable dehydration in industry. Kampmann<sup>22)</sup> showed that, in coal mines, after an exposure from 4 to 8 a.m., the average rate of rehydration was 60%, independently of the total quantity of sweat produced and that 95% of the subjects had a rate of rehydration higher than 40%.

On the basis of these values, it was proposed that the maximum water loss, taking into account the normal compensations, be equal to:

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

#### *The PHS model*

The Required Sweat Rate model was revised using all

the new algorithms described above and was renamed Predicted Heat Strain (PHS) as it predicts the physiological parameters (sweat rate and rectal temperature) minute per minute according to the working conditions.

Two articles describe more in detail the criteria for calculation of the limiting durations of exposure<sup>23)</sup> and the validation of the PHS model<sup>24)</sup>.

## **Validation of Model PHS**

#### *Choice of the data*

The database described above was used for the validation of new PHS model.

From the 95% confidence intervals at the primary parameters, it was determined that the model could be validated in the ranges of values reported in Table 1.

For the validation, data points were selected for each experiment by using the following criteria:

- For sweat rate: average sweat rate on the whole experiment;
- For the rectal temperature, selection of points (one per hour) in each experiment.

#### *Validation based on the laboratory experiments*

Table 2 gives the results of the linear regressions between the observed and predicted rectal temperatures and the observed and predicted sweat rates for the laboratory experiments and the experiments in the field.

Figure 1 compares the predicted and observed sweat rates. The 95% confidence limits of the values were calculated in the polar co-ordinates so that uncertainty between predicted values and observed values is proportional to the observed sweat rate.

The average polar line equation was:

$$SW_{\text{obs}} = 0.918 * SW_{\text{p}}$$

(with the 95% confidence interval (CI: 0.540–1.523))

Figure 1 shows that the regression line is practically identical to the line at 45°C.

Three points are higher than the upper limit of the 95% confidence interval. They come from three different partners and show the influence of the interindividual differences. Indeed, for identical experiments but with other subjects, the data are above or below the straight regression line and in the confidence interval. The same remark can be made for points located below the lower limit of the 95% confidence interval.

Figure 2 compares the observed and predicted rectal temperatures.

**Table 1. Ranges of validity for the PHS model**

	$t_a$ °C	$P_a$ kPa	$t_r-t_a$ °C	$v_a$ m/s	M W	$I_{cl}$ Clo
Min	15	0	0	0	100	0.1
Max	50	4,5	60	3	450	1.0

**Table 2. Regressions between observed and predicted (PHS) values of rectal temperature and sweat rate**

	Laboratory experiments	Field experiments
	Sweat rate (g/h)	
N	672	237
Observed (m ± s)	424 ± 172	317 ± 187
Predicted (m ± s)	451 ± 154	344 ± 132
R	0.7601	0.7448
alpha	0.918	0.851
alpha CI95%	0.540–1.523	0.328–1.936
Obs. –Pred. (m ± s)	–27,5 ± 114,1	–26,7 ± 125,1
Rectal temperature (°C)		
N	1937	1028
Observed (m ± s)	37,45 ± 0.47	37,40 ± 0.44
Predicted (m ± s)	37,46 ± 0.47	37,40 ± 0.34
R	0.6585	0.5940
alpha	1.000	1.000
alpha CI95%	0.980–1.020	0.981–1.019
Obs. –Pred. (m ± s)	–0.01 ± 0.39	–0.01 ± 0.36

The averages and standard deviations of the observed and predicted values are almost identical. The coefficient of correlation is equal to 0.66 and is lower than that obtained for sweat rate.

The average polar line equation is:

$$t_{re\ obs} = 1.000 * t_{re\ p} \quad (\text{with CI: } 0.979\text{--}1.020)$$

Again, the points located apart from the 95% confidence interval (Fig. 3) are due to the interindividual differences.

*Validation based on the field experiments*

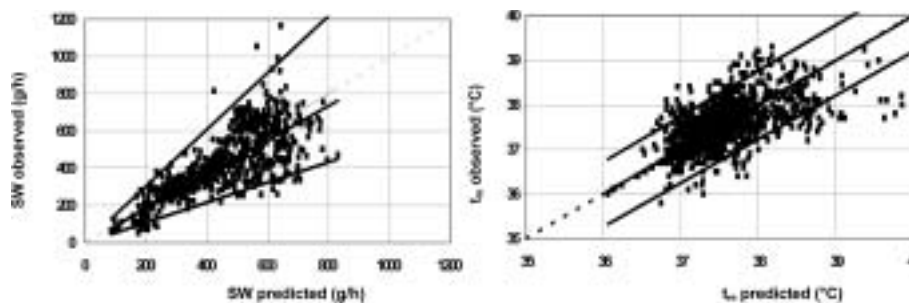
Figures 3 and 4 compare the observed and predicted sweat rate (Fig. 3) and rectal temperature (Fig. 4) for the experiments in the field.

The precision of climatic and physiological measurements being generally lower for the experiments in the field, the correlations between the observed and predicted values tend to be lower with larger confidence intervals at 95%.

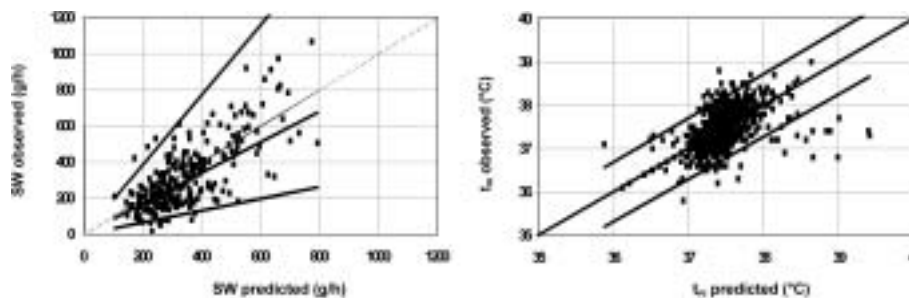
The average polar line equations are:

$$SW_{obs} = 0.851 * SW_p \quad (\text{with CI: } 0.328\text{--}1.936)$$

$$t_{re\ obs} = 1.000 * t_{re\ p} \quad (\text{with CI: } 0.981\text{--}1.019)$$



**Figs. 1 and 2. Observed vs predicted values of sweat rate and rectal temperature (with the 95% confidence interval) for the 672 laboratory experiments.**



**Figs. 3 and 4. Observed vs predicted values of sweat rate and rectal temperature (with the 95% confidence interval) for the 237 field experiments.**

## Strategy for the Management of the Working Conditions to Heat

The developed strategy follows the principles of the SOBANE strategy<sup>25)</sup>. The approach can be summarized by the graphics of Fig. 5. The strategy includes 4 levels of intervention strictly directed towards prevention, since the main objective of the evaluation of the risks related to the thermal environment is not to assess the risks, but to prevent or eliminate it or, at least, to reduce it at the lowest reasonable level.

The 4 levels of the strategy can be described briefly as follows:

### *Level 1: Screening*

On the first level, all or the majority of the factors of risk or problems are detected in order to provide a first overall picture of the work situation. During a 2h meeting with some workers and members of the local management, the working conditions are systematically reviewed concerning the aspects of safety, health, wellbeing, ease of work and productivity. The conclusions relate, in particular, to the existence of complaints concerning the climatic conditions and to the need for additional investigations, but also to any aspect of the work situation, in order to improve comprehensively and coherently the living conditions.

### *Level 2: Observation*

The second level is now focused on the climatic conditions of work. It is again implemented by the persons from the work situation (workers and management). It remains simple to understand and use by the untrained people and benefit from what the users know best, namely their working conditions in the course of time, the technical process, the characteristics of the hot or cold sources and the possibilities for prevention measures. The method helps them to structure and systematize their approach, so that it is not only based on perceptions and opinions.

### *Level 3: Analysis*

The third level is conceived to be implemented with the assistance of an occupational health (OH) practitioner such as an occupational physician, an industrial hygienist, an ergonomist... having, at least, a basic training in the management of thermal problems. The method still uses concepts and techniques generally known in the field, thus avoiding sophisticated considerations such as evaporative efficiency or wettedness. When measurements are required to optimize prevention measures, they are simple and can

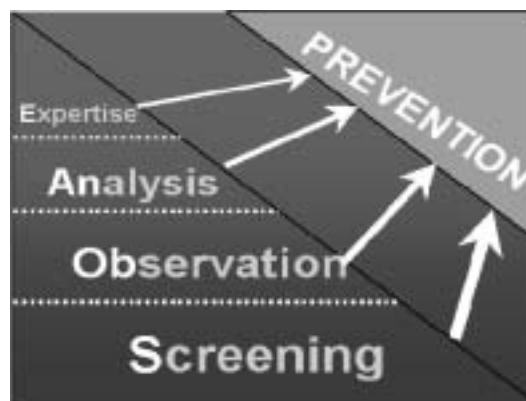


Fig. 5. Illustration of the strategy of prevention.

be made with instruments inexpensive, easy of use and easily available in the field.

The method remains oriented towards prevention and is consequently based on measurements and indices that make possible to better identify the causes of the problems and the means of solving them. Here, the PHS model is used as a black box.

At the end of the Analysis, the users should be able to determine whether the problems are solved or whether a more complete Expertise is Required.

### *Level 4: Expertise*

This level can be required in very complex cases where satisfactory solutions still could not be found after the detailed Analysis. It must be carried out with the assistance of a specialist who should be able to decide the best way of answering the specific problem. Consequently, the methodology to use, the measurements to make, the evaluation to carry out will vary according to the problem and the method is limited to a broad outline of what this Expertise study should necessarily include and provide.

The final version of the strategy was prepared and validated in the field with the contribution of 53 OH practitioners. An article describing in detail the strategy was published<sup>26)</sup> and the strategy is now accepted as the ISO standard 15265<sup>27)</sup>.

## Conclusions

The Predicted Heat Strain model is derived from an in-depth revision of the previous Required Sweat Rate model and new algorithms were developed, based on the scientific literature concerning the convection and evaporation heat transfers, the skin temperature, the heat distribution between the skin and the core of the body, the rectal temperature...

The maximum criteria of sweat rate, dehydration and increase in the core temperature were also re-examined.

The Predicted Heat Strain (PHS) makes it possible to predict the sweat rate and the rectal temperature for an average subject and to calculate the duration limit of exposure to protect 50% and 95% from the population of the workers.

The PHS model was validated starting from data coming from 672 experiments undertaken in laboratory previously by the various partners of this research. The model proves to provide reasonably accurate predictions, taking into account the interindividual differences in physiological response to heat. The results were also tested in 237 experiments in the field: the prediction accuracy can be regarded as satisfactory, considering the fact that the precision of the primary data collected in the field is generally reduced.

The PHS model has replaced entirely the required sweat rate model in the revised version of the ISO 7933 standard<sup>28)</sup>.

It is clear that the model is very much more sophisticated than the previous one and the users must be invited to use it as a simple black box or computer program, allowing to predict the physiological evolution of a person when exposed to an environment described by the 6 primary parameters of air temperature and humidity, radiation, air velocity, metabolic rate and clothing insulation.

This research made it possible to provide the people exposed themselves and the OH practitioners with a set of complementary methods clear and simple to use, likely to enable them to protect the workers more effectively, more rapidly and more economically.

These methods should also make it possible to guarantee the same level of safety and health in all industries in all the countries and in particular in the countries of the south which are mostly concerned with these working conditions.

The development of more adequate standards should pave the road towards a European directive specific on the evaluation of the working conditions to heat or, at least, should clarify the requirements of the European Directive 89/654<sup>29)</sup> about the minimal conditions of safety and health for the work places.

## Acknowledgements

The PHS model was developed during a research sponsored by the Program BIOMED II of the European Commission of the European Union and conducted by some of the prominent European specialists in thermal physiology:

- G. Alfano, DETEC c/o FAC. Ingegneria, Piazzale Tecchio 80, I - 80125 Napoli
- E. Den Hartog, TNO Human Factors, Dept. of Work

Environment, Thermal Physiology Group, Kampweg 5, P.O. Box 23, NL - 3769 ZG Soesterberg

· H. Gebhardt, Institut für Arbeitsmedizin, Sicherheitstechnik und Ergonomie, Corneliusstr.31. D - 42329 Wuppertal

· I. Holmér, National Institute of Working Life (NIWL), S - 171 84 Solna

· B. Griefahn and P. Mehnert, Institute für Arbeitsphysiologie an der Universität Dortmund, Ardeystr. 67, D - 44139 Dortmund

· B. Kampmann, Institut für Arbeitswissenschaften der Ruhrkohle Aktiengesellschaft, Hülshof 28, D-44369 Dortmund

· K. Parsons, G. Havenith, Thermal Human Environments Laboratory, Loughborough University, Ashby Road, The U.K. - Loughborough, Leicestershire LE11 3TU, the U.K.

## References

- 1) ISO 7933 (1989) Hot environments—Analytical determination and interpretation of thermal stress using calculation of required sweat rate. ISO, Geneva.
- 2) ISO 9920 (1995) Estimate of the thermal characteristics of a clothing. ISO, Geneva.
- 3) Havenith G, Holmér I, den Hartog EA, Parsons KC (1999) Clothing evaporative heat resistance-proposal for improved representation in standards and models. *Ann Occup Hyg* **43**, 339–46.
- 4) Holmér I, Nilsson H, Havenith G, Parsons KC (1999) Clothing convective heat exchange. Proposal for improved representation in standards and models. *Ann Occup Hyg* **43**, 329–38.
- 5) Parsons K.C, Havenith G, Holmér I, Nilsson H, Malchaire J (1999) The effects of wind and human movement on the heat and vapour transfer properties of clothing. *Ann Occup Hyg* **43**, 347–52.
- 6) Mehnert P, Malchaire J, Kampmann B, Piette A, Griefahn B, Gebhardt HJ (2000) Prediction of the average skin temperature in warm and hot environments. *Euro J Appl Physiol* **82**, 52–60.
- 7) Livingstone SD, Nolan RW, Cain JB, Keefe AA (1994) Effect of working in hot environments on respiratory air temperatures. *Euro J Appl Physiol* **69**, 98–101.
- 8) Varena P (1986) Computation of respiratory heat exchanges. *Euro J Appl Physiol* **61**, 1586–9.
- 9) Kähkönen E (1993) Comparison and error analysis of instrumentation and methods for assessment of neutral and hot environment on the basis of ISO standards, 101, Kuopio University Publications, Kuopio, Finland.
- 10) Colin J, Timbal J, Houdas Y, Boutelier C, Guieu J (1971) Computation of mean body temperature from rectal and skin temperatures. *J Appl Physiol* **31**, 484–9.

- 11) Edwards RJ, Belyavin AJ, Harrison MH (1978) Core temperature measurement in man. *Aviat Space Environ Med* November, 1289–94.
- 12) Malchaire J (1991) Predicted sweat rate in fluctuating thermal conditions. *Eur J Appl Physiol* **63**, 282–7.
- 13) Araki T, Inoue M, Fujiwara H (1979) Experimental studies on sweating for exercise prescription: total body sweat rate in relation to workload in physically trained adult males. *J Hum Ergol* **8**, 91–9.
- 14) Gosselin RE (1947) Rates of sweating in the desert. In: *Physiology of man in the desert*, Adolph EF (Ed.), 44, Interscience Publishers, New York.
- 15) Havenith G (1997) Individual heat stress response. Doctoral thesis, Catholic University of Nijmegen.
- 16) Saltin B, Hermansen L (1966) Oesophageal, rectal, and muscle temperature during exercise. *J Appl Physiol* **21**, 1757–62.
- 17) WHO Scientific Group (1969) Health factors involved in working under conditions of heat stress. Tech Rep series No 412, WHO, Geneva.
- 18) Wyndham CH, Strydom NB, Morrison JF, Williams CG, Bredell GAG, Maritz JS, Munro A (1965) Criteria for physiological limits for work in heat. *J Appl Physiol* **20**, 37–45.
- 19) Wyndham CH, Heyns AJ (1973) The probability of heat stroke developing at different levels of heat stress. *Arch Sci Physiol* **27**, 545–62.
- 20) Kampmann B (1997a) Working paper GT2/13 of BIOMED project BMH4-CT96-0648 “HEAT”: Risk analysis for one colliery of Ruhrkohle AG in 1995, Catholic University of Louvain, Brussels.
- 21) Candas V, Libert JP, Brandenberger G (1985) Hydration during exercise—Effects on thermal and cardiovascular adjustments. *Eur J Appl Physiol* **55**, 113–22.
- 22) Kampmann B (1997b) Working paper GT2/12 of BIOMED project BMH4-CT96-0648 “HEAT”: Rehydration in field experiments and laboratory investigations, Catholic University of Louvain, Brussels.
- 23) Malchaire J, Kampmann B, Havenith G, Mehnert P, Gebhardt HJ (2000) Criteria for estimating acceptable exposure times in hot work environment, a review. *Int Arch Occup Environ Health* **73**, 215–20.
- 24) Malchaire J, Piette A, Kampmann B, Mehnert P, Gebhardt H, Havenith G, den Hartog E, Holmér I, Parsons K, Alfano G, Griefahn B (2001) Development and validation of the predicted heat strain model. *Ann Occup Hyg* **45**, 123–35.
- 25) Malchaire J (1997) Stratégie générale de prévention des risques professionnels. *Cahiers de Médecine du travail*. XXXIV, 3–4, 159–66 (in French).
- 26) Malchaire J, Gebhardt HJ, Piette A (1999) Strategy for evaluation and prevention of risk due to work in thermal environment. *Ann Occup Hyg*, **43**, 367–76.
- 27) ISO 15265 (2004) Ergonomics of the thermal environment—Risk assessment strategy for the prevention of stress or discomfort in thermal working conditions. ISO, Geneva.
- 28) ISO 7933 (2004) Hot environments—Analytical determination and interpretation of thermal stress using calculation of the predicted heat strain. ISO, Geneva.
- 29) Council Directive 89/654/EEC (1989) Concerning the minimum safety and health requirements for the workplace (First individual directive within the meaning of Article 16(1) of Directive 89/191/EEC). *Official Journal of the European Communities*, No L/393/1–12, Brussels.