



# Heat Stress and Protective Clothing: an Emerging Approach from the United States

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**There is little doubt that heat stress affects many workers adversely and that protective clothing generally adds to the burden. The ACGIH threshold limit value for heat stress is the guiding document for evaluation of heat stress in the United States. Adjustment factors have been used to reflect the change in heat stress imposed by different clothing ensembles. While the first proposed factors started with limited experimental data and professional judgment, heat balance methods in the laboratory have yielded better estimates of adjustment factors and for a wider selection of ensembles. These same experiments have provided the starting point to accounting for nonporous clothing in heat balance evaluation schemes such as required sweat rate. Proposed changes to the ACGIH TLV have been mentioned and a framework for thinking about controls presented. © 1999 British Occupational Hygiene Society.**

*Keywords:* heat stress; threshold limit value; clothing; United States of America

## INTRODUCTION

Working from the premise that heat stress can and does cause serious heat-related disorders (Withey, 1999), the next questions that occupational health and safety professionals must face are when should we be concerned and what should we do? In terms of when, the standards of good professional practice were described by Parsons (1993; 1999). In the United States, the National Institute for Occupational Safety and Health (NIOSH, 1986) as a government agency takes one leadership role while the American Conference of Governmental Industrial Hygienists (ACGIH, 1999) assumes another role in efforts to promote heat stress practices in the workplace. As an important note, the ACGIH has overlapping membership with, and moral support from, the American Industrial Hygiene Association. In addition, there are industry groups such as the Electric Power Research Institute (Bernard, Kenney, O'Brien and Hanes, 1991) that address health and safety practices appropriate to their industries.

Major efforts in the United States were directed to chronic exposures to heat stress and adopted the goal of the World Health Organization (WHO, 1969) to control deep body temperature below 38°C. Using and expanding on the work of Lind (1963),

NIOSH professionals (Dukes-Dobos and Henschel, 1973) developed the recommended exposure limit based on the wet bulb globe temperature index and metabolic rate. The ACGIH threshold limit value (TLV) for heat stress was first adopted in 1972. Because protective clothing affects the level of heat stress, investigators have reported the effects of various ensembles in terms of changes in WBGT (Bernard, Kenney and Balint, 1986; Bernard *et al.*, 1991; Cortés-Vizcaino and Bernard, 1999; Kenney, 1987; O'Connor and Bernard, 1999; Ramsey, 1978). The ACGIH proposed adjustment factors for four clothing ensembles in the 1990 TLV, which are those in draft 5 of the BSI Standard, and adopted there in 1991.

Just because a workplace condition may be above a threshold for chronic heat stress does not mean that there is undue risk to workers for a limited period of time. The ACGIH TLV and similar exposure threshold schemes use time-weighted averaging to account for time-varying exposures. TWAs, however, do not provide good guidance for a time-limited exposure. To determine safe exposure times, Belding and Hatch, (1955) proposed a rational index for heat stress that could be used to estimate a safe exposure time. The US Navy uses physiological exposure limits (PHELs) to limit the exposure time based on the WBGT and metabolic rate, and these are used in some workplaces. Other WBGT-based exposure limits have been proposed, such as those

Received 20 November 1998; in final form 20 May 1999.  
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recommended by the Electric Power Research Institute (Bernard *et al.*, 1991). While not commonly used in the United States, the state-of-the-art rational index is reflected in ISO 7933 (1989) and BS EN 12515 (1997). This method was adapted by the Electric Power Research Institute and makes provisions for protective clothing ensembles common to the nuclear power industry (Bernard *et al.*, 1991).

Taking a different approach, the upcoming notice of intended change for the ACGIH TLV (1999) will formalize physiological monitoring as an alternative for demonstrating adequate protection of workers. I suspect that a primary driver for this approach was the difficulty in predicting the impact of protective clothing on heat stress. A problem with physiological monitoring is that it is fundamentally reactive. That is, exposures must occur before a decision can be made about the level of stress. Therefore, its use as a predictive tool is problematic.

For the second question of what to do, once a work scenario is determined to be above a threshold for heat stress, controls are appropriate. These include broadly applied general controls plus job specific controls as necessary (Bernard, 1995). General controls are training, heat stress hygiene practices, and medical surveillance. Job specific controls are the traditional hierarchy of engineering controls, administrative controls and personal protection.

In the continuing effort to understand the effects of protective clothing in heat stress, the heat balance analysis provides a framework for both evaluating the level of heat stress in the workplace as well as for the laboratory evaluation of protective clothing ensembles. The principal purpose of this paper is to present a rationale for the assignment of WBGT-based adjustments for protective clothing ensembles and how data might be developed to account for a broader range of clothing materials and construction practices within the rational method of required sweat rate analysis. The results for a variety of commercially available ensembles are described.

### RATIONALE

As pointed out by Havenith (1999), heat balance analysis is a method to account for the exchange of energy between a person and the environment, which includes the work demands and the effects of clothing. The following equation is a formulation of two fundamental features. (See Appendix A for symbol definitions.) The left side is an expression of the maximum rate of evaporative cooling that can be supported by the combination of clothing and environment. The right side is an expression of the required rate of evaporative cooling to maintain thermal equilibrium.

$$(P_{sk} - P_a)/R_{e-t} = (M - W) + (C + E)_{res} + (T_{db} - T_{sk})/I_t \quad (1)$$

Under any given set of circumstances, the maximum evaporative cooling may be less than, equal to, or greater than the required evaporative cooling. The maximum rate of evaporative cooling decreases with ambient water vapor pressure and with increases in the total evaporative resistance of the clothing plus air layer. The required rate of evaporative cooling is the sum of the internally generated metabolic heat less the external work accomplished plus the net heat exchange in the lungs plus the net dry heat exchange. In an environment with little radiant heat, the dry heat exchange increases with increasing air temperature and decreases with total clothing insulation (intrinsic plus air layer).

Under controlled laboratory conditions, a person can be exposed to a combination of environmental conditions and work rate for a given clothing ensemble such that the person has no trouble achieving thermal equilibrium. After a physiological steady state is established, the thermal balance can be challenged by any number of methods (Barker, Kini and Bernard, 1999; Kenney, Hyde and Bernard, 1993). These include any combination of increasing humidity (water vapor pressure), air temperature and metabolic rate. The 5 min increments are small so that a quasi steady state is maintained until thermal equilibrium is lost. At this point, body core temperature begins to increase steadily.

The critical conditions for the experimental trial are those environmental and metabolic parameters that exist just prior to the observed increase in core temperature. From the critical conditions, a critical WBGT for the ensemble can be determined as well as most of the data in Eq. (2).

$$(P_{sk} - P_a)/R_{e-t} = (M - W) + (C + E)_{res} + (T_{db} - T_{sk})/I_t - S \quad (2)$$

$S$  is the rate of heat storage, which is theoretically zero, and practically small, prior to the critical condition. By estimating a value for  $I_t$ , the only unknown is the total evaporative resistance,  $R_{e-t}$ .

With values for  $I_t$  and  $R_{e-t}$ , estimates of  $F_{cl}$  and  $F_{pcl}$  as used in the required sweat analysis schemes can be made experimentally for the clothing ensembles. These estimates are based on Eqs. (3) and (4) (Barker *et al.*, 1999).

$$F_{cl} = 1/[(h_r + h_c)I_t] \quad (3)$$

$$F_{plc} = 1/16.7h_cR_{e-t} \quad (4)$$

Table 1. List of clothing ensembles with clothing adjustment factors (CAF) as °C-WBGT, estimated total insulation (°C m<sup>2</sup>/W) and computed total evaporative resistance (kPa m<sup>2</sup>/W), and  $F_{cl}$  and  $F_{pcl}$ <sup>a</sup>

Ensemble description	CAF	$I_t$ ( $R_{e-t}$ )	$F_{cl}$ ( $F_{pcl}$ )
Work clothes: a standard ensemble that includes a 4 oz cotton shirt with long sleeves and 8 oz cotton pants; this is the reference ensemble for setting clothing adjustment factors	0.0	0.084 (0.0131)	0.85 (0.53)
Cloth coveralls (CC): a standard configuration of anticontamination coveralls with a hood and hand and foot coverings; the fabric is either a cotton or cotton/polyester blend with weights of about 8 to 9 oz	3.5	0.107 (0.0159)	0.64 (0.40)
Cloth coveralls over scrub suit: the configuration described as CC plus a set of 2 oz cloth underalls (aka surgical scrub suit)	4.5	0.143 (0.0228)	0.49 (0.29)
Double cloth coveralls: the configuration described as CC plus a second set of the cloth coveralls only	5.0		
SMS polypropylene coveralls: limited-use coveralls with hood (particle barrier only) made from a spunbonded, meltblown polypropylene	-1.0	0.086 (0.0109)	0.82 (0.64)
MB polyethylene coveralls: limited use coveralls with hood (particle barrier only) made from a meltblown polyethylene (Tyvek <sup>®</sup> 1422A)	2.0	0.086 (0.0164)	0.82 (0.440)
Polyester coveralls: light-weight polyester (98% Nylon) (3 oz) coveralls worn with a hood of the same material (ProTech2000)	0	- (0.0127)	
Polyester coveralls with scrubs: light-weight polyester coveralls and hood worn over a typical surgical scrub suit (cotton or cotton/polyester blend)	3.0	0.122 (0.0196)	0.58 (0.34)
Water-barrier, vapor-permeable coveralls: limited-use overall with hood made from tri-laminate fabric with a tetrafluoroethylene microporous film	6.0		
Water-barrier, vapor-permeable coveralls: overall with hood made from tri-laminate fabric with a microporous film	2.5	0.086 (0.0176)	0.83 (0.39)
Vapor-barrier coveralls: coveralls and hood made of light weight fabrics designed for limited use worn over cloth coveralls; typical fabrics might be a polyethylene coated spunbonded polyethylene or a polyvinylchloride	8.5		
Encapsulating suit or turn-out gear: total encapsulating suits (e.g. Level A); re-usable, whole-body chemical protective suits; fire-fighter turn-out gear	11		
Flame-retardant shirt and pants: long-sleeve Zirpo <sup>®</sup> wool shirt and pants made from FR8 <sup>®</sup> treated cotton fabric	0.5	0.084 (0.0141)	0.86 (0.51)
Flame-retardant shirt and pants: long-sleeve shirt and pants made from FR9 <sup>®</sup> treated cotton fabric	1.0	0.083 (0.0144)	0.87 (0.50)
Flame-retardant shirt and pants w/single-layer jacket: long-sleeve shirt and pants with jacket made from FR9 treated cotton fabric	2.0	0.119 (0.0169)	0.61 (0.44)
Flame-retardant shirt and pants w/double-layer jacket: long-sleeve shirt and pants with a double-layer jacket made from FR9 treated cotton fabric	3.0	0.137 (0.0175)	0.52 (0.39)

<sup>a</sup> Fabric weights reported in mean ounces per square yard (oz/yd<sup>2</sup>, 1 oz/yd<sup>2</sup> = 33.9 g/m<sup>2</sup> approximately). Temperatures for the adjustment factors have been rounded to the nearest 0.5°C. Estimated total insulation has been reduced to 55% of intrinsic insulation plus air layer insulation at 0.5 m/s. Overall, this has a small effect on evaporative resistance,  $F_{pcl}$  and required evaporative cooling (Barker *et al.*, 1999; Bernard & Matheen, 1999).

## METHODS

Typically, five subjects (mostly men) were used to evaluate any one clothing ensemble described in Table 1. Because the reported data were collected over a number of years, the groups of subjects changed among the ensembles. (See Barker *et al.*, 1999 for subject characteristics.)

The experiments were conducted in a climatic chamber where air movement was 0.5 m/s.

Heart rate (HR) was monitored with a clinical EKG system. Core temperature ( $T_{re}$ ) was measured using a flexible thermistor inserted 10 cm beyond the anal sphincter muscle. Skin temperature was measured using surface thermistors at four points (chest, upper arm, thigh and calf). Metabolic rate during treadmill walking was determined from oxygen consumption.

The protocols were designed to cause heat storage by increasing the heat load from radiation and convection or metabolic rate, and to reduce the maximum rate of evaporative cooling available. For the

protocols in which the climate was changed, treadmill speed and grade were set to elicit a metabolic rate of about 160 W/m<sup>2</sup> at a zero grade (level). The four protocols used in the studies are described below. The set of completed protocols for the ensembles were different.

During each trial, the subjects were allowed to drink a commercial fluid replacement drink as desired. Data were monitored continuously and recorded every min. The trial was stopped when (1) a clear rise in  $T_{re}$  associated with a loss of thermal equilibrium occurred (e.g. subject's  $T_{re}$  increased at least 0.1°C for three consecutive 5 min intervals), (2) 140 min was reached or (3) the subject wished to stop. For subject safety, a trial would also be stopped if  $T_{re}$  exceeded 39°C or heart rate exceeded 90% of maximum age-estimated heart rate.

### Hot, dry climates

The starting dry bulb and psychrometric wet bulb temperatures were 34 and 18°C (20% relative

humidity). Once a physiological steady state was achieved (steady heart rate and core temperature), the ambient temperature was increased approximately 1°C every 5 min while the relative humidity was maintained at about 20%. The ambient water vapor pressure also increased very slowly.

#### *Warm, humid climates*

The starting dry bulb and psychrometric wet bulb temperatures were 34 and 18°C (20% relative humidity). Once a physiological steady state was achieved, the psychrometric wet bulb temperature was increased approximately 0.7°C every 5 min until the relative humidity reached 70%. Then, the dry bulb temperature was increased about 0.7°C every 5 min while the relative humidity was maintained at 70%. As a result, the ambient water vapor pressure increased steadily during this protocol.

#### *50% relative humidity climates*

The starting dry bulb and psychrometric wet bulb temperatures were 34 and 25.5°C (50% relative humidity). Once a physiological steady state was achieved, the ambient temperature was increased approximately 0.8°C every 5 min while the relative humidity was maintained at 50%. As a result, the ambient water vapor pressure also increased.

#### *Metabolic rate, fixed climate*

In the metabolic rate protocol,  $T_{db}$  was set at 32°C and  $T_{pwb}$  was set at 26°C (60% relative humidity) for the experiment. Treadmill speed and grade were set to elicit a low metabolic rate (about 120 W/m<sup>2</sup>) and were held constant until the subject reached a physiological steady state. Then treadmill speed was increased 0.045 m/s every min. This protocol was developed in our laboratory to directly explore the effects of heat stress on sustainable metabolic rate, which is a marker for productivity.

## RESULTS AND DISCUSSION

Experimental trials based on establishing critical conditions (highest level of heat stress at which thermal balance could be maintained) were used to establish the effects of protective clothing on heat stress. This approach has been used by several investigators to explore heat exchange coefficients for use in rational heat stress models and was used by both Kenney and Bernard to develop WBGT adjustments.

Considering WBGT adjustments first, the basic approach is to treat ordinary work clothes as the baseline ensemble. This was done to reflect the fact that the WBGT-based thresholds were developed for work clothes. Any difference in equilibrium WBGT would be due to the difference in clothing effects. As reported in Table 1, the clothing adjust-

ment factor (CAF) represents the equivalent increase in environmental WBGT that the clothing represents (ACGIH — Notice of Intended Change, 1999; Bernard *et al.*, 1991; O'Connor & Bernard, 1999). This is the opposite use of the original ACGIH TLV and the proposed BSI, where the adjustment is used to lower the threshold value instead of correcting the observed WBGT value. In so far as the clothing effect is concerned, there is no real difference in the approaches other than opposite signs.

Kenney (1987) used the hot/dry and warm/humid protocols to establish critical WBGTs. He reported critical WBGT values as two standard deviations below the mean for all subjects for each ensemble and each protocol. Using work clothes as the baseline, the following adjustment factors evolve from his report: Cotton Coveralls, 3.6°C; Double Cotton Coveralls, 6.2°C; and Polyethylene-coated Tyvek<sup>®</sup> over Cotton Coveralls (vapor-barrier), 10.6°C. Because the lower limit was aggressively set (1.65 standard deviations would have met the protection goal) and because there was somewhat more variability in the data as the clothing became more restrictive of evaporative cooling, these values may overstate the effects of the clothing. When looking at the mean values (Kenney, personal communication), the differences follow those reported in Table 1 more closely.

For cloth coveralls, the Table 1 value was 3.5°C, which is similar to the difference reported by Kenney in 1987. It contrasts with the 2°C used by the TLV and draft BSI, and first proposed by Bernard *et al.* (1986), who used some experimental data, established practice and professional judgment to arrive at a value.

Kenney (1987) reported a value of 6.2°C for double cloth coveralls, while the difference between averages was closer to 5°C. The ACGIH physical agents committee interpreted double coveralls as a winter work uniform and assigned a value of 4°C, which was originally the value in Bernard *et al.* (1986).

The value for cloth coveralls over scrub suit was estimated by the author as an intermediate value favoring the double coverall value.

Using data for water-barrier, vapor-permeable coveralls with a membrane produced by Gore and Associates (Kenney *et al.*, 1993), a 6°C factor can be estimated. The water-barrier, vapor-permeable value was also used by the ACGIH, BSI and Bernard *et al.* (1986, 1991).

The ACGIH used 10°C for vapor-barrier clothing based on the results of Paull and Rosenthal (1987), who suggested a value of 11°C by contrasting the WBGT inside and outside of a total encapsulating suit and the data from Kenney (1987) with values reduced by two standard deviations. Reneau and Bishop (1996) supported the 10°C value from a

review of high heat stress experiments with the military chemical warfare ensemble. This may represent an overestimate of the value for light-weight vapor-barrier coveralls over cloth coveralls, which is 8.5°C in Table 1, based on other reported data (Kenney *et al.*, 1993).

The remaining data were reported by O'Connor and Bernard (1999) from studies performed at the University of South Florida. Most of the WBGT adjustments were based on the hot/dry and warm/humid protocols, with some including the 50% relative humidity protocol. The FR9® ensembles were based on the results of the 50% relative humidity protocol alone.

The values of  $I_t$  and  $R_{e-t}$  in Table 1 were based on data collected at the University of South Florida.  $I_t$  was estimated using the data on intrinsic clothing insulation plus the insulation due to the boundary layer of air with ambient movement of 0.5 m/s (for instance, see Parsons, 1993), and then multiplying by 0.55 as a coarse adjustment for confounding factors. Large differences in the values for  $I_t$  result in small changes in  $R_{e-t}$ , so the approximation is not important (Barker *et al.*, 1999; Bernard and Matheen, 1999). From the approximation of total insulation, total evaporative resistance was computed from Eq. (2). An average value was determined for each protocol and then the average of the protocols was reported in Table 1.

Based on these data and others from the University of South Florida, a linear relationship between total evaporative resistance and clothing adjustment factor was found (O'Connor & Bernard, 1999).

For each trial, a value for clothing factors ( $F_{cl}$  and  $F_{pcl}$ ) was determined from Eqs. (3) and (4). The average for all trials was provided in the table. When working with nonporous fabrics, the directly estimated values might be used in the required sweat rate analysis (Barker *et al.*, 1999; Bernard *et al.*, 1991). These estimated values can be used as a starting point until other data become available using techniques to more clearly parse out the intrinsic contributions of the clothing elements to insulation and evaporative resistance. A spreadsheet method for required sweat rate has been developed that uses these factors.

#### COMMENTS ON THE ACGIH TLV AND HEAT STRESS MANAGEMENT

The traditional role of the ACGIH TLV for heat stress was to place a stake in the ground with regard to the potential for excessive levels of heat stress if the exposures were sustained over an 8 h day. Explicit in the exposure limits was the goal to limit core temperature to 38°C. The documentation also provided some guidance on the determination of metabolic rate to help make the decision better.

With some data available on protective clothing, reductions in the threshold value were recommended. Ultimately, the physical agents committee reminded industrial hygienists that protective clothing requirements should be reviewed by someone knowledgeable about the effects. Like NIOSH, the TLV provided a list of measures that could be taken to manage the heat stress exposure.

The ACGIH TLV booklet for 1999 has a notice of intended change for the heat stress TLV. The new title will be the TLV for Heat Stress and Strain. Fundamentally, it extends the thought process behind the current TLV. First, it recommends that heat stress controls be considered whenever vapor-barrier or encapsulating clothing is worn. Second, if the TLV is exceeded then controls should be implemented. Then if high work demands or unacclimatized workers are present, the potential for excessive heat stress is there; and again controls should be considered. As a final consideration, if medical surveillance indicates excessive physiological strain or heat-related disorders, then controls are necessary. It goes on to suggest physiological markers and symptoms of heat disorders that require attention. Most importantly, it opens the door for physiological monitoring to assess the level of stress and demonstrate adequate worker protection.

The protective clothing and equipment committee of the American Industrial Hygiene Association is revising its manual on the selection and use of chemical protective clothing. A chapter is being prepared by the author along with Dukes-Dobos. Under consideration is a chart to suggest stay times based on ambient globe temperature and metabolic rate while wearing vapor-barrier, total encapsulating suits. This chart is provided as Fig. 1.

In an attempt to bring a framework to controls, the following outline was suggested (Bernard, 1995). When there is a reasonable belief that workers may be exposed to heat stress above the ACGIH TLV for unacclimatized people, then general controls should be implemented. These include:

- Training: preplacement and annual Heat stress hygiene practices
  - Selfdetermination of exposure and work pace
  - Adequate fluid replacement
  - Maintaining a healthy diet and lifestyle
  - Monitoring and acting on chronic and acute disease
  - Adjusting expectations during acclimatization
- Medical surveillance
  - Preplacement and periodic physicals
  - Monitoring individuals for sentinel health events
  - Monitoring the population for sentinel health events

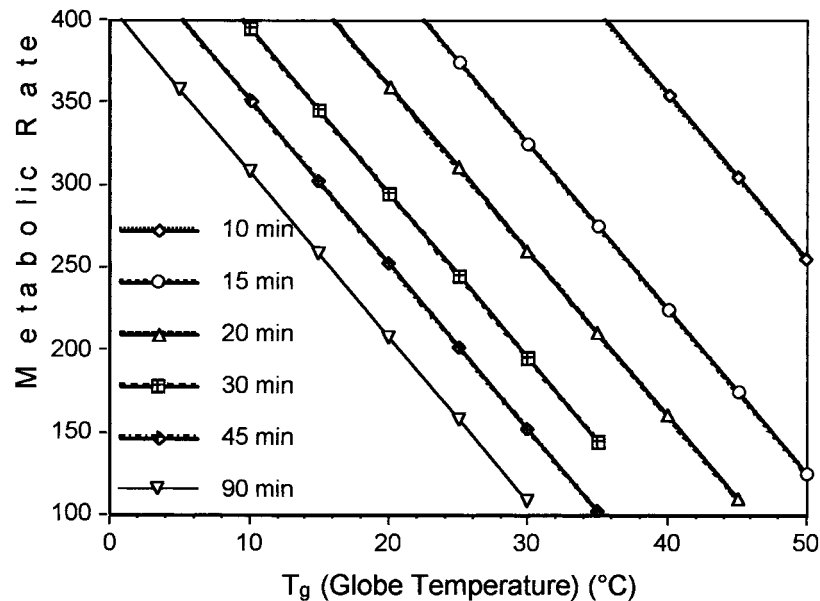


Fig. 1. Chart recommending stay times while wearing vapor-barrier, total encapsulating clothing as a function of globe temperature and metabolic rate.

As a note on heat stress hygiene practices, they are an individual responsibility, but management must minimize the barriers.

When exposures substantially above the TLV for acclimatized workers may occur, then job specific controls are necessary. These may include:

**Engineering controls**

- Reducing metabolic rate
- Changing clothing requirements
- Modifying the environmental conditions

**Administrative controls**

- Specification of work times
- Providing adequate recovery
- Physiological and symptoms monitoring
- Buddy system and other work practices

**Personal protection**

- Personal cooling systems
- Reflective clothing

By understanding the change in physiological burden that protective clothing may add, a better determination of whether heat stress will be a factor in the work can be made. In addition, the understanding supports methods such as the required sweat rate to point toward alternative clothing ensembles under engineering controls and the prescription of safe work times under administrative controls.

*Acknowledgements*—I wish to thank the Clothing Science Group conference organizers for their invitation and hospitality in June 1998. Support for the research described here has come from the Electric Power Research Institute, DuPont Company, Cotton Incorporated, ICONCO, and

Interstate Nuclear Services among others. The cooperation of the test participants, student assistants and staff are also appreciated. Finally, I wish to express my continuing gratitude to Francis N. Dukes-Dobos for his collaboration.

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## APPENDIX

### Symbols

$P_{sk}$	average water vapor pressure on the skin
$P_a$	ambient water vapor pressure
$R_{e-t}$	total evaporative resistance of the clothing including the air layer
$M$	metabolic rate (internal heat generation)
$W$	external work accomplished
$(C + E)_{res}$	combined convective and evaporative heat exchange in the lungs
$T_{db}$	dry bulb (air) temperature
$T_{sk}$	average skin temperature
$I_t$	total insulation of the clothing plus air layer
$S$	rate of heat storage in the body (increases body temperature)