Heat Stress in Occupational Work

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Occupational heat stress causes health and safety problems. Heat indexes should be used in the workplace to prevent harmful heat exposure.

Although industrial development might result in processes with improved heat-shielding, hot work sites are likely to persist to a relatively large degree in *eg* the iron, glass, rubber, aluminum and paper pulp industries. Exposure to heat in industry is also frequently associated with more or less heavy physical exertion, leading to additional, physiologically induced internal heat production (1). Depending partly upon this combination of heat loading, various problems arise with regard to the health and safety of the worker. In order to direct attention to these problems, a summary of the physiological reactions in heat stress are given in this report and a simple index is recommended to be used for a critical analysis and evaluation of the work sites.

PHYSIOLOGICAL RESPONSE TO HEAT LOADING

Thermal balance: Man is capable of maintaining his thermal balance under a wide variety of climatic conditions. A complex system of reactions regulates body temperature and balances heat gains and heat losses. The body's heat production and heat exchange with its surroundings can be simply described using the following formula:

$$+M \pm C \pm R - E = \pm S;$$

where M represents the organism's heat production, C, R and E stand for heat exchange by convection, radiation and evaporation of perspiration respectively. S is the amount of heat lost or stored in the body with an attendant decline or increase in body temperature. Thus, heat exchange with the surroundings mainly takes place by means of convection, radiation and evaporation. In normal circumstances, heat exchange by means of conduction is slight enough to be regarded as negligible.

According to the above formula for the thermal balance, the body is capable of losing or receiving heat by *convection*. If the temperature of ambient air is higher than the body's surface temperature, heat gain results, whereas heat is lost if the air temperature is lower than the body's surface temperature. This exchange in one direction or the other is also proportional to the air velocity at the surface of the body. Heat exchange by *radiation* is similarly dependent upon the difference between the body's surface temperature and the temperature of ambient surfaces. The heat gain by this route might be considerable in a hot industrial environment. Heat is eliminated by *evaporation of water* from the body. This evaporation is continuous from the lungs and skin; evaporation from skin is increased by sweating. In hot conditions, sweating is the most efficient mechanism for heat elimination, the magnitude of which is dependent on the difference between the water vapor pressure at the skin surface and in the ambient air. Thus, evaporation increases with increasing air velocity. High relative humidity, with a high vapor pressure in the ambient air, can therefore severely restrict the body's ability to dissipate the heat which may have been formed through muscular exertion or gained from the surroundings, *eg* in the form of radiation or convection heat.

The thermal balance can be maintained within rather wide limits, thanks to physiological variations including changes in blood circulation through the skin which lead to changes in convection (C), radiation (R) and sweat production (E).

A large amount of heat is generated in conjunction with muscular exertion. Since the efficiency of muscular work amounts to a maximum of 25 percent, more than 75 percent of the energy obtained from metabolic degradation degenerates to heat. Heat production amounting to 200—250 kcal/h (800—1000 kJ/h) is not uncommon in occupational work. This degree of heat production would be sufficient to raise the temperature of the body by about 4°/h, if heat regulatory mechanisms failed to operate. Body temperature increases during the first 30—45 minutes of any physical exertion, thereafter stabilizing at some level, when and if thermal balance is attained (Figure 1) (2). The level of body temperature is governed by the intensity of work performed and by the individual's physical work capacity in such a manner that a person's body temperature levels off at about 38.0°C when working at an intensity corresponding to half of his maximal oxygen uptake (3, 4, 5). Thermal balance is only attained after this initial phase which encompasses the storage of heat in the body.

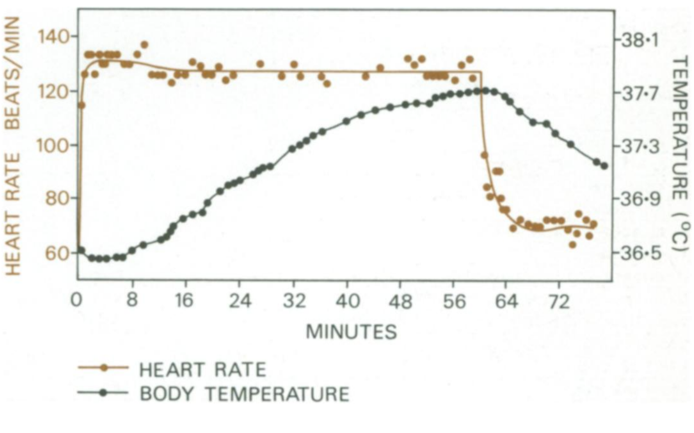


Figure 1. Heart rate (color) and body temperature (black) in a subject during continuous work on a bicycle ergometer (work load: 160 watts; 960 kpm/min). From Christensen (2).

Increased heart rate: Physiological responses to heat loading include increased skin circulation which facilitates the dissipation of heat from the skin to the surroundings. This adjustment of blood circulation is associated with an increased pulse rate. Extremely fast-increasing pulse rates are frequently reported from hot work sites. These high pulse rates are mainly induced by radiant heat, probably as a purely reflexive response (Figure 2).

Sweating: Another readily discernible physiological response to heat loading is sweating. The degree of sweating is governed by the degree of heat loading. Figure 3 illustrates a series of experiments conducted by Nielsen in 1938 (6). Among other things, the intensity of sweating was measured during these experiments. At the lowest temperature, sweating accounted for about 30 percent of heat dissipation and convection and radiation for 70 percent. At the highest room temperature, the organism absorbed heat from the surroundings (convection and radiation), since the temperature of the skin was lower than that of the surroundings. Heat dissipation due to evaporation of water must accurately compensate for changes in convection and radiation as a condition for the maintenance of thermal balance under such varying conditions. The figure clearly shows that such a compensation did take place. The perspiration amounted to about 150 g/h at the lowest room temperature and to about 700 g/h at the highest.

The experiments cited above show that heat dissipation during work mainly takes place through adjustment of skin circulation and sweat secretion (7, 8, 9, 10, 11, 12 p 505, 13). Blood is the main carrier of heat from working muscles to the skin. Since the specific heat of blood is high, *viz* 0.9 kcal (3.8 kJ) per degree and kg, this transport can take place without the temperature of the blood undergoing any drastic changes. When the temperature gradient between arterial blood and the skin is great, a given amount of heat can be transferred with a lesser skin circulation than when the temperature gradient is small. Sweat production can be regulated by a change in the number of sweat glands in action or by a change in the rate of secretion (7).

Dehydration: As implied above, heavy work leads to large fluid losses, especially if the work takes place in a hot climate.

Figure 2. Heart rate in a melter during three work days in a steelworks.

1 = Smelting of ore
2 = Tapping
3 = Changing of electrode
4 = Slagging
5 = Liming
6 = Rest
7 = Sampling
8 = Repair work
9 = Cleaning work

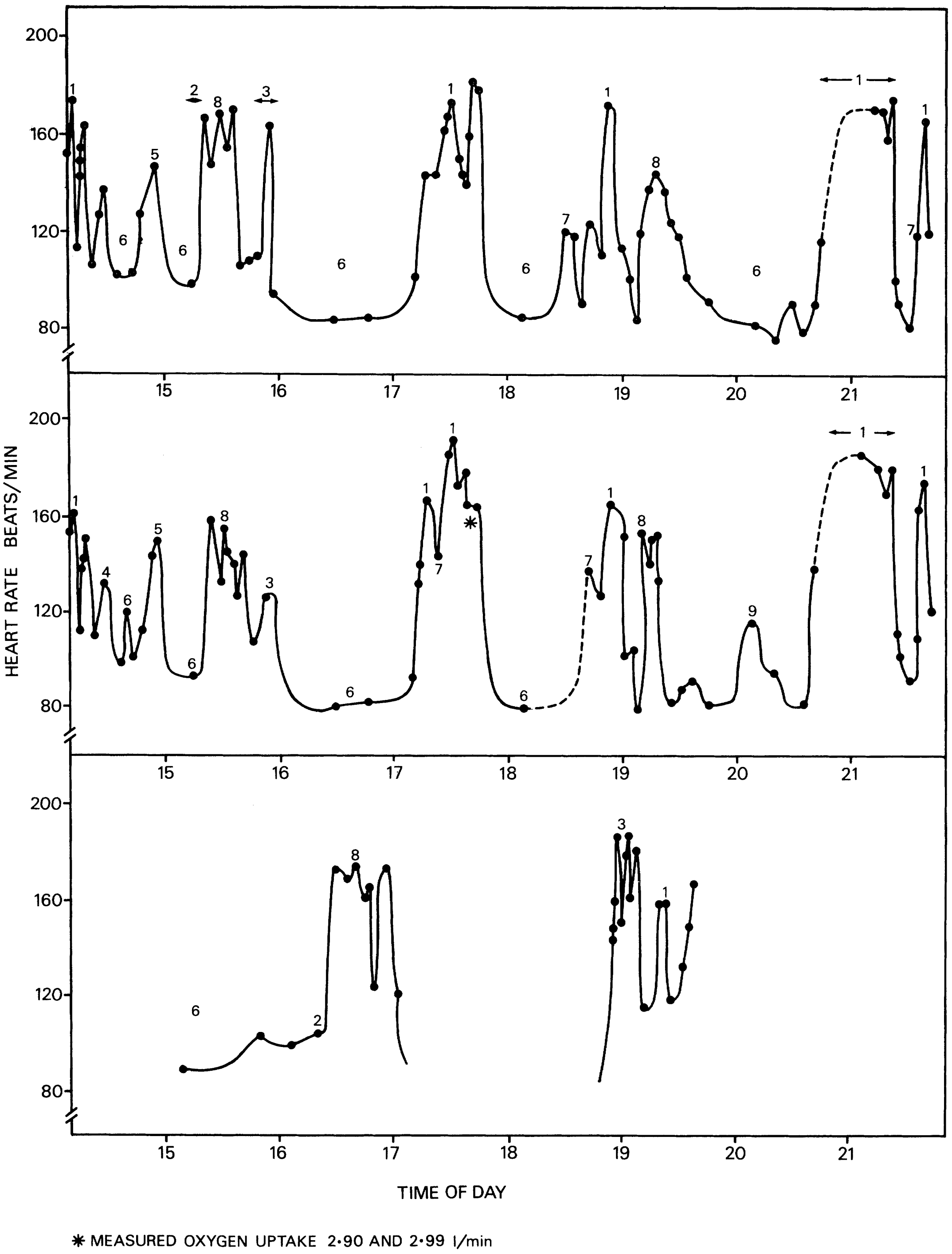
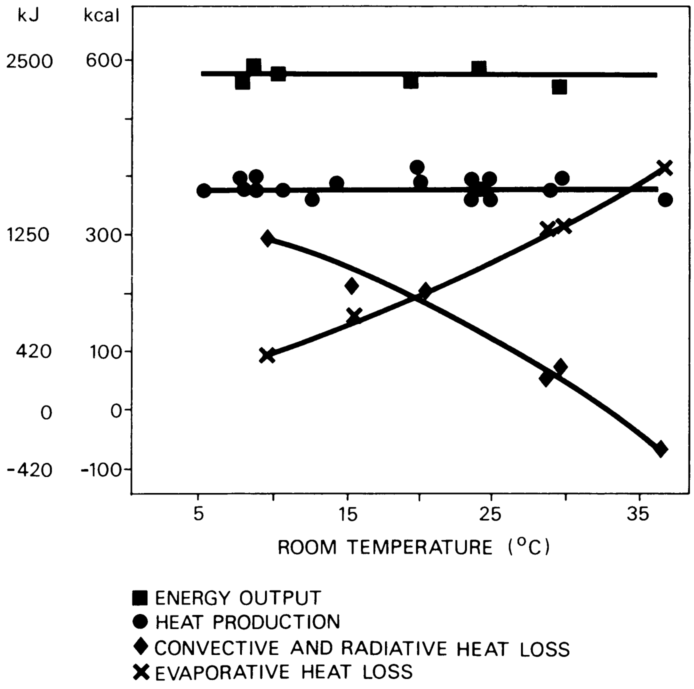


Figure 3. Heat exchange during work (150 watts; 900 kpm/min) at different room temperatures in a nude subject. Measurements made after about 1 hour's work. Modified from Nielsen (6).



Fluid losses due to sweating may amount to 5—6 l/work shift or more during severe heat loading (14, 15, 16). The salt content of sweat is low, but nevertheless protracted sweating may result in salt depletion. Uncompensated sweating leads to dehydration, *ie* a deficiency of water in the body. The degree of dehydration can be estimated by measuring the decline in body weight. Man tends to compensate poorly for fluid losses caused by sweating. This tendency is reinforced in work, and only half of the water loss is sometimes compensated by voluntary drinking (17). As dehydration corresponding to 5—6 percent of body weight has a serious effect on the circulation, a dehydrated person may consequently be unable to work, and dehydration corresponding to only 1 percent of body weight produces a measurable impairment in physical work capacity and in circulatory response in the upright position (orthostatic tolerance). Involuntary dehydration may amount to close to 2 percent of body weight. The dehydration may lead *eg* to a 10 beats/min increase in pulse rate per percent of dehydration (18). Body temperature rises by about 0.2° per percent of dehydration.

Evaluation of total heat load: There are work steps in certain trades in which heavy exertion is combined with exposure to heat. The normal relationship between work heaviness and body temperature is then upset, since heat dissipation is unable to keep pace with heat production. The additional load on the organism caused by a hot environment can be illustrated by having a subject perform a standard work program on a bicycle ergometer in a normal climate and at the hot work site in question. Table 1 illustrates such an experiment (19). As the table shows, heat exposure produced a pulse rate which was about 60 beats/min higher at the hot work site than in normal conditions and increased the rectal and the skin temperatures by 1°C and 5°C respectively.

Table 1. Effect of environmental temperature on human response to standard work on a bicycle ergometer. The measurements were made after 45 minutes of work. From (19).

Work load W	Air temp °C	Rectal temp °C	Mean skin temp °C	Heart rate beats/min	Heat production kcal/m² per h	kJ/m² per h	kg	Weight loss percent of body weight
100	19—20	37.8	32.8	104	160	670	0.25	0.3
100	32—44	38.8	37.6	166	160	670	1.15	1.6

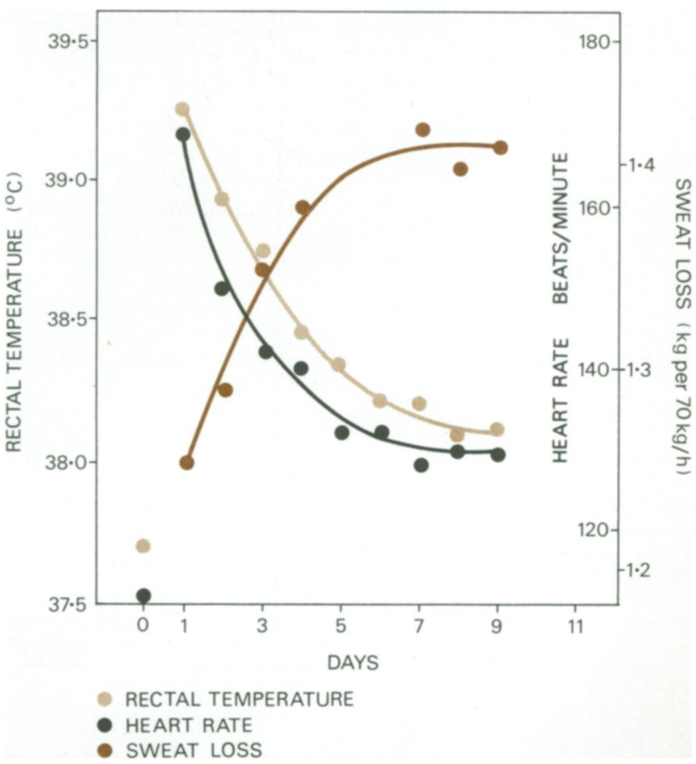
Using the following formula (20, 21), the amount of heat C which can be removed from the body in certain given conditions can be calculated:

$$C = \frac{M_s}{A(T_r - T_s)};$$

where M_s is the heat produced by metabolism per hour; A is body area in m²; T_r is rectal temperature and T_s is average skin temperature. The maximum value for C has been specified at 78 kcal/m² (330 kJ/m²) per hour for every 1°C of difference between the rectal and skin temperature. If this value is applied to the experimental results reported in Table 1, it is obvious that thermal balance can not be maintained at the work site in question without a rise in body temperature. Thermal balance can only be attained in such circumstances if the work intensity (heat production) is reduced or pauses inserted in which the exposed subject has an opportunity to cool off. Another and more attractive solution is to improve climatic conditions at the work site. This can be achieved by means of technical changes in the work process or by personal protective equipment.

Acclimatization: The ability to tolerate heat can be enhanced by means of acclimatization. This entails a series of physiological changes in the individual, particularly during the first week of heat loading. The effect of acclimatization is easily observed. Thus, a lower pulse rate, a lower body temperature and greater sweat production are ultimately obtained. One and the same combination of heat exposure and physical work was used each day during the acclimatization illustrated in Figure 4 (22). In acclimatization, the salt content of sweat tends to decline (23). It should be emphasized that physical training also produces an automatic enhancement of heat tolerance (24). An individual's degree of acclimatization is always of decisive importance with regard to his ability to work in hot surroundings without developing signs of heat distress. Acclimatization may be lost relatively quickly *eg* in conjunction with holidays, sick leave or other absence. After an absence of some time, the individual should be given an opportunity to become reacclimatized under moderate heat stress before returning to daily work in hot surroundings,

Figure 4. Mean rectal temperature, heart rate, and sweat loss in a group of men during a 9-day acclimatization to heat. On day 0 they worked for 100 min at a rate of energy expenditure of 300 kcal/h (about 1200 kJ/h) in a cool climate. On the following days they worked in a hot climate (48.9°C dry-bulb and 26.7°C wet-bulb temperature). Modified from Lind and Bass (22).



especially if this work is physically taxing. A reacclimatization period of at least four days is recommended when absences exceed nine days (25). This can be achieved by allowing a worker to start off by performing only 50 percent of heat-loaded work. The amount of work is then gradually increased until complete heat loading is achieved after about a week.

THERMAL INDEX—PREREQUISITES, STRUCTURE AND USEFULNESS

Thus, heat stress produces a number of apparent physiological reactions. They are, however, both difficult to measure and to use for the assessment of thermal load in an industrial work situation. For this reason, so-called heat stress indices have been introduced in the past 50 years and are supposed to reasonably mirror the heat load on the individual. The different indices are usually determined with the aid of physical measurement of ordinary air temperature (dry bulb), radiant temperature (globe), relative humidity (wet bulb) and air velocity (25). A measure of the individual's metabolism is also often included, *ie* work heaviness must be measured or estimated.

At best a thermal index is capable of weighing the body's own heat production and heat exchange with the environment in such a manner that the index indicates the individual's physiological, thermal response in a given situation or reflects the subjective estimate of comfort in the existing climate. Unfortunately, the desire to obtain good index validity has tended to complicate the index in such a way that its practical usefulness is reduced at the same time as the risk of misinterpretation increases. The practical difficulties in obtaining representative measurement values in many industrial environments have not always been taken into account. Difficulties in this context frequently govern the degree of usefulness. This is readily apparent when it is realized that a worker performs work of varying heaviness and moves in thermally differing zones at the work site at the same time as temperature may vary with time. Movement in itself generates air currents which are not recorded by static instruments. Radiation temperature, in particular, may change quickly with time. This produces difficulties in measurement technique as long as a comparatively sluggish globe thermometer is used. Inter-individual differences in clothing are also part of the picture. In addition, the work processes often require protective clothing, a circumstance which makes the practical assessment of the heat situation in individual cases even more difficult. Finally, people do not all respond in the same way in a given physiological or psychological situation. The degree of acclimatization plays a role, as well as individual differences in the number of sweat glands, the size of the body area and differences in physical work capability.

In a comparative discussion, rather recently, of a number of indices, Kerslake (13) pointed out certain fundamental differences between them. Some are based on physiological observations (*eg* P4SR), others on subjective preference (ET) or on analytical arguments on heat exchange (HSI). The definitions of abbreviations and the varying degree of complexity of the indices mentioned here are shown in Table 2. Some indices can be calculated from simple nomograms, whereas others require the combination of several nomograms. An index may also occasionally call for formula corrections of the information obtained from nomograms. There are also indices which are based on a comparatively simple formula, such as WBGT. Work heaviness is taken into account in the more complicated indices, making possible direct comparisons between different combinations of thermal loading and work heaviness. The more simply devised indices make it necessary to relate values to work heaviness. This means that such indices must comprise multiple tolerance limits related to work heaviness.

An index can actually be used primarily to indicate situations comprising serious heat loading so that harmful effects on health can be avoided. Principally simple indices can thus be used for routine assessment of heat loading. The WBGT has the desirable simplicity and is therefore the most reasonable recommendation for practical industrial purposes.

The WBGT index (26) was introduced in 1957. According to Botsford's description (27), the index was intended to replace the so-called Effective Temperature including Radiation index, ETR. However, the formula computation of the WBGT index has been changing somewhat over the years. A large number of versions have actually been used, as noted by *eg* Botsford, who described five different formulas for the WBGT (27). Therefore, the WBGT must necessarily be adequately defined, as the different formulas do not produce identical WBGT values when applied to the same given thermal condition.

In 1946 (28) Minard recommended an original formula based on aspirated wet-bulb temperature, but he also introduced an alternative based on natural wet-bulb temperature. Subsequent studies (29, 28) resulted in the current American recommendation (30, 25) of a formula for outdoor work with solar radiation and another for indoor or outdoor work without solar radiation. Both formulas are based on "natural wet-bulb temperature". This term refers to the temperature which is obtained with an unventilated wet-bulb thermometer unprotected against radiation. Unfortunately, a 30-min equilibrium time is required with such a thermometer, making it awkward to use in practical work. The wetted wick around the thermometer must also be kept white and clean, a circumstance which may be difficult to attain in dusty environments.

Since no parameter of air velocity is included in the "ventilated" WBGT, it apparently gives consideration to air velocity only through the influence of air movements on the globe temperature. From the practical point of measuring this is an advantage, since air velocity is difficult to assess (31). Since a natural wet-bulb thermometer is not protected against radiation and is normally only exposed to rather modest air currents, it always displays higher values in principle than a ventilated wet-bulb thermometer. Rather large differences may be noted in certain cases (32), but recent Swedish studies (33) suggest that the difference in WBGT values obtained according to the following two formulas nevertheless is rather slight at air velocities exceeding 0.5 m/s:

$$\mathrm{WBGT} = 0.7\ \mathrm{pWB} + 0.3\ \mathrm{GT}$$
$$\mathrm{WBGT} = 0.7\ \mathrm{nWB} + 0.2\ \mathrm{GT} + 0.1\ \mathrm{DB}$$

DB = dry-bulb temperature; pWB = psychrometer wet-bulb temperature; nWB = natural wet-bulb temperature; GT = globe temperature (Vernon globe).

PROPOSAL FOR A SWEDISH TEMPERATURE INDEX

The Swedish temperature index, hereafter designated SWBGT (Swedish Wet Bulb-Globe Temperature Index), is based on the American WBGT index (Wet Bulb-Globe Temperature Index) (30) and on Recommendations for a Standard for Work in Hot Environments (25). The SWBGT entails a modification of the WBGT measurement method. The natural wet-bulb temperature is replaced by the psychrometric wet-bulb temperature and air velocity measurement is added (33).

SWBGT is determined as follows:

1) At air velocities ≥ 0.5 m/s:
   $\mathrm{SWBGT} = 0.7 \times \mathrm{pWB} + 0.3 \times \mathrm{GT}$
2) At air velocities < 0.5 m/s:
   $\mathrm{SWBGT} = 0.7 \times \mathrm{pWB} + 0.3 \times \mathrm{GT} + 2$
   where pWB = psychrometric wet-bulb temperature (°C) and GT = globe temperature (°C). Generally, formula 1) will be used because at most work places with high heat exposure the air velocity usually exceeds 0.5 m/s.

In the determination of SWBGT, a measurement of psychrometric wet-bulb temperature, globe temperature and air velocity is required. However, even dry-bulb temperature, *ie* air temperature, should be measured so that it becomes easier to assess the measures necessary to reduce a heat load which may be too high.

Table 2. Construction of different indices. HSI = Belding & Hatch Heat Stress Index; P4SR = Predicted 4-Hour Sweat Rate; WBGT = Wet Bulb-Globe Temperature; ET = Effective Temperature; CET = Corrected Effective Temperature.

Index	Nomogram		Formula		Work load included	
	Simple	Complex	Simple	Complex	Simple	Complex
HSI	—	+	—	(+)	+	—
P4SR	—	+	+	—	—	+
WBGT	—	—	+	—	—	—
ET, CET	+	—	—	—	—	—

Limit values: The limit values specified are recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) (30). The values are supposed to represent conditions to which most workers can be exposed daily without harmful effects. The limit values are based on the assumption that almost all acclimatized and fully clothed workers with an appropriate fluid and salt intake should be able to work under the given work conditions without their body temperatures rising above 38°C (16). Due to large inter-individual variations in heat tolerance, however, some people may be uncomfortable or exposed to potential injury even below the specified limit values. Such individuals may be recognized as sufferers from heart disease, renal failure and possibly other observable disorders and should therefore be followed with stringent medical checkups. On the other hand, other people may be able to stand higher heat stress. However, no worker should be allowed to continue working when his body temperature rises above 38.0°C.

The specified limit values are intended for practical use in industry, and measurements and evaluations of results obtained should be carried out by people trained for the purpose.

In Figure 5 the ACGIH limit values (30) are specified for heat exposure with different degrees of work severity and with varying periods of work and rest. The values apply to reasonably acclimatized persons. Values 1—2°C less should be applied to partially acclimatized or unacclimatized persons. Common work loads are exemplified in Figure 6.

The permissible values for heat exposure according to Figure 5 are based on the assumption that the rest site has about the same heat exposure as the work site. If the rest site has an exposure corresponding to an SWBGT of 24° or less, rest pauses can be reduced by 25 percent, from the temperature point of view. The permissible exposure for continuous work refers to a 5-day work week and an 8-hour day with a 15-min break in the morning and afternoon and a lunch break of about 30 min. Higher exposure may be permitted if additional breaks are inserted. Unintentional pauses, such as waiting time and the like, can be regarded as rest pauses, in addition to ordinary breaks, in the determination of heat loading.

Figure 5. Permissible heat exposure expressed in SWBGT °C for different work loads. Modified from ACGIH (30). Light work corresponds to an oxygen uptake of ≦ 1.0 l/min (≈ 5 kcal/min ≈ 20 kJ/min), moderately heavy work to > 1.0—1.5 l/min (≈ 5—7.5 kcal/min ≈ 20—30 kJ/min), and heavy work to > 1.5 l/min (≈ 7.5 kcal/min ≈ 30 kJ/min). From Åstrand & Rodahl pp 438—450 (12).

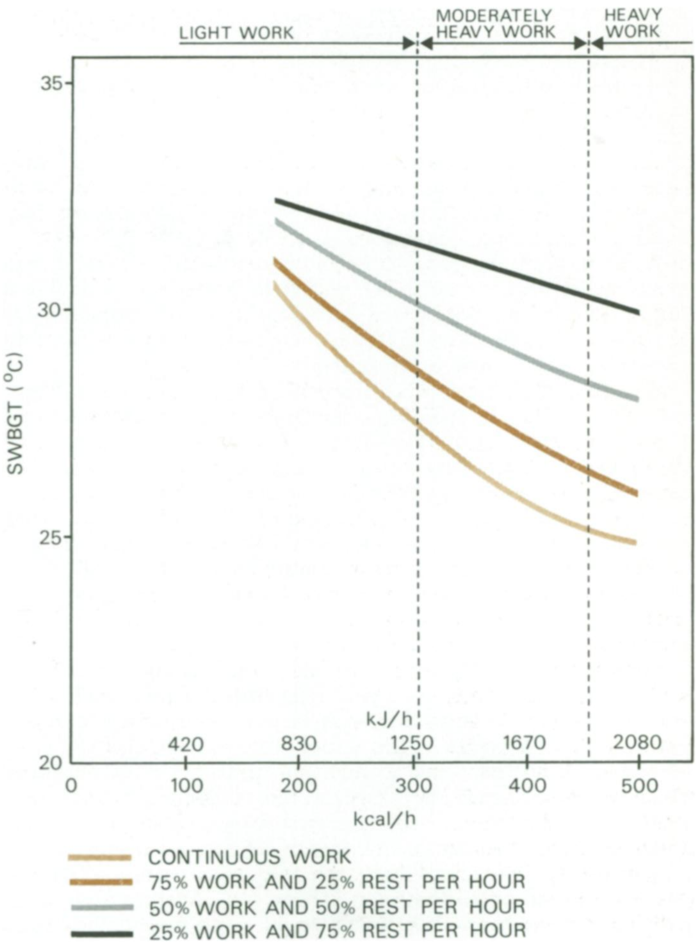
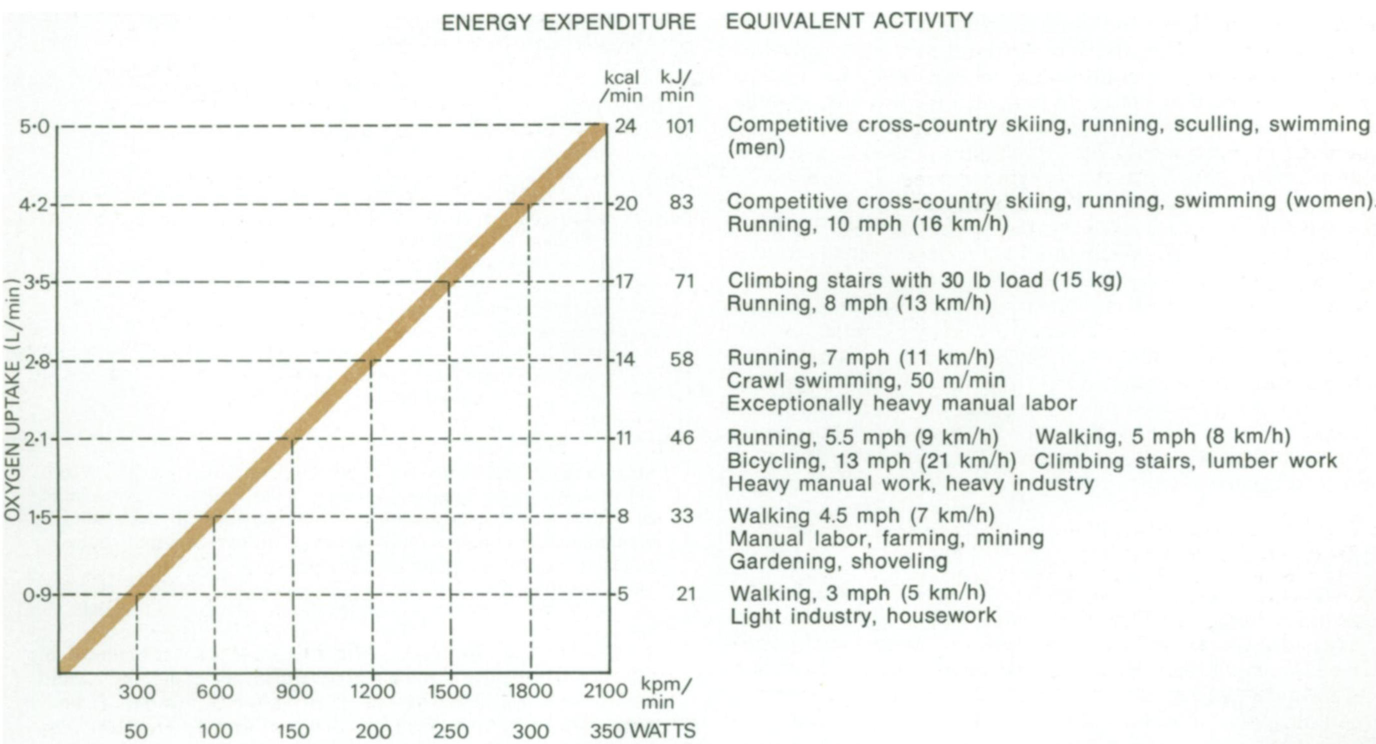


Figure 6. Bicycle ergometer work in kpm/min or watts and equivalent physical activities. Energy expenditure for "equivalent activity" is only approximate and is meant merely as a general guide. It depends, among other things, on the weight of the subject. The examples listed are based on the average male with a body weight of 160 lb (70—75 kg). From Åstrand & Rodahl p 364 (12).



With varying exposure the time weighted average for the SWBGT is determined as follows:

3) $$SWBGT_{mean} = \frac{SWBGT_1 \times t_1 + SWBGT_2 \times t_2 + \ldots + SWBGT_n \times t_n}{t_1 + t_2 \ldots\ldots\ldots + t_n}$$

in which $SWBGT_1$, $SWBGT_2$, ... $SWBGT_n$ are SWBGT values for the different work and rest sites respectively determined according to equations 1) or 2) and t_1, t_2, ... t_n are the duration of work or of breaks (in min) at each respective site.

The same equation, 3), is used in the determination of heat exposure when exposure and work load vary. A final mean value, weighted for time, is used in the evaluation of heat loading according to Figure 5.

When exposure is reasonably homogenous for several hours or throughout an entire shift, the SWBGT might be calculated for one hour and considered representative for the shift. On the other hand the SWBGT shall be determined over a 2-hour period when exposure is intermittent.

It should be noted that the SWBGT recommended here primarily applies to the assessment of average thermal loading during a work shift. However, a work situation may be characterized either by rather constant heat loading or by intermittent and often rather severe heat loading succeded by periods with a relatively light load. It should also be noted that exposure for an hour or so to very intense heat may have a highly unfavorable effect on the individual without the total time-compensated 8-hour exposure being excessive. In other words, the views advanced here should be applied with caution in individual situations.

The ability to withstand extreme heat mainly depends on two mechanisms, *viz* the skin's sensitivity to pain and sensitivity to the accumulation of heat in the body. Pain sensations from the skin arise at a skin temperature of about 45°C (34). This means that exposure to high temperatures must naturally be brief. At present, there are no generally accepted recommendations on the tolerable duration of exposure to extreme heat. In exposure durations exceeding 15 min when direct pain sensations are less significant, the tolerance is limited by the heat accumulation in the body instead (35). Studies have been made which suggest that this type of exposure may have a more fatiguing and far-reaching effect on the worker, producing symptoms such as insomnia, than brief, intense exposure (36).

The SWBGT takes into account certain but not all of the factors which affect an individual's ability to withstand heat. Age, sex, somatic constitution, the state of health and probably other factors, in addition to work severity, acclimatization and clothing, jointly result in the spread found in the workers heat tolerance or comfort perception (37, 38, 39, 40). Therefore, it should be realized that about 90 percent of a working population can be covered by a simple index assessment. The remaining 10 percent should be the subject of additional measurements when the limit for tolerable values is approached (41). As previously mentioned in this context, body temperature should then be measured. It is assumed that 38.0°C is the body temperature limit which should not be exceeded in work subject to heat exposure.

In the evaluation of risks caused by heat stress, the wide variations already mentioned should be kept in mind. Cardiovascular disease and functional derangement of the kidneys should especially be watched for in persons whose occupations expose them to heat loading of varying severity. Transfer to jobs with moderate heat loading should routinely be considered for workers aged 45—50 unless special circumstance point to an even earlier transfer.

CONCLUSION

Heat stress in occupational work, not unusual in Sweden, causes problems concerning the health and safety of workers. However, up to now, heat stress has not been satisfactorily analyzed or evaluated. Measurement methods and guidelines for evaluating heat stress have been described in this article. Many additional steps must be taken in order to ensure that the heat load on the worker does not exceed certain recommended limit values.

References and Notes:

1. About one year ago, a working group was formed in Sweden for the purpose of 1) reviewing the available literature on heat stress, 2) drawing up guidelines on the basis thereof, for an evaluation of heat stress in Swedish occupational work, and 3) advising the choice of monitoring methods. The present article is based on a recently published report of the group's work: O Axelson, U Eriksson, L Olander, M Rehn and I Åstrand, *Arbete och hälsa 4* (Arbetarskyddsverket, Stockholm, 1974).
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