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Limiting Metabolic Rate (Thermal Work Limit) as an Index of Thermal Stress

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The development of a rational heat stress index called thermal work limit (TWL) is presented. TWL is defined as the limiting (or maximum) sustainable metabolic rate that euhydrated, acclimatized individuals can maintain in a specific thermal environment, within a safe deep body core temperature ($< 38.20^{\circ}\text{C}$) and sweat rate ($< 1.2 \text{ kg/hr}^{-1}$). The index has been developed using published experimental studies of human heat transfer, and established heat and moisture transfer equations through clothing. Clothing parameters can be varied and the protocol can be extended to unacclimatized workers. The index is designed specifically for self-paced workers and does not rely on estimation of actual metabolic rates, a process that is difficult and subject to considerable error. The index has been introduced into several large industrial operations located well inside the tropics, resulting in a substantial and sustained fall in the incidence of heat illness. Guidelines for TWL are proposed along with recommended interventions. TWL has application to professionals from both the human and engineering sciences, as it allows not only thermal strain to be evaluated, but also the productivity decrement due to heat (seen as a reduced sustainable metabolic rate) and the impact of various strategies such as improved local ventilation or refrigeration to be quantitatively assessed.

Keywords Heat, Stress, Strain, Index, Limit, Work Rate, Self-Pacing

Thermal stress, with its attendant problems of heat illness, safety incidents, lowered productivity, poor morale, and higher costs, affects many industrial operations. Over the past 80 years, many heat stress indices have been developed to assist with the management of these problems. Some of these have been developed for particular industries and the majority are empirically derived. More recently, attempts have been made to develop so-called “rational” heat stress indices. These attempt to model some central physiological parameter that indicates thermal strain on the body (e.g., deep body core temperature, sweat

rate, or heart rate) and provide a recommended limit. Empirical heat stress indices frequently have little validity outside the narrow range of conditions for which they were designed, and are often revised “in-house” to fit particular circumstances. Problems with a rational heat stress index, such as ISO 7933,⁽¹⁾ become evident when it is introduced into a workplace where workers are mobile and work at varying tasks and metabolic rates during their work shift.

“Externally paced work” has been traditional in many industries and countries. However, the increasing degree of mechanization of heavy tasks and the “duty of care” style of legislation that has now become common are resulting in better-informed workers and in redesigned jobs that do promote self-pacing for persons under considerable heat stress.

In this article, self-paced workers are defined as those who can and do regulate their own work rate, are not subject to excessive peer or supervisor pressure or monetary incentives, and are well educated about the issues of working in heat and the importance of self-pacing. The “environment” is defined as the full combination of factors outside the worker that lead to heat stress: air temperature and humidity, radiant heat, wind speed, barometric pressure, and clothing.

The need for a heat stress index designed primarily for self-paced workers has led to the development of the thermal work limit (TWL). TWL is defined as the limiting (or maximum) sustainable metabolic rate that euhydrated, acclimatized individuals can maintain in a specific thermal environment within safe limits of both deep body core temperature ($< 38.20^{\circ}\text{C}$) and sweat rate ($< 1.2 \text{ kg/hr}^{-1}$).

TWL and its accompanying management protocols^(2–3) have been introduced into several industrial operations where workers are subject to thermal stress. Approximately 1400 persons work in these locations with over 10 million man-shifts being worked between 1965 and 1995 at wet bulb temperatures in excess of 28°C .⁽⁴⁾ There has been a significant reduction in heat illness since the introduction of TWL.⁽⁵⁾ The previous heat management protocol (used from 1942 to 1996) was based on the Predicted Four Hour Sweat Rate and involved a reduction in the shift length from 8 to 6 hours when the environmental

conditions exceeded a certain threshold. With the introduction of 12-hour shifts in the operations, the cost and productivity loss of a shortened shift was severe. The introduction of new protocols allowing full shifts to be worked has therefore improved the productivity, as well as the safety, of the operations.

Most existing heat stress indices have significant shortcomings, being technically flawed, inappropriate, impractical, or poorly applied.^(6–9) Typical problems include:

- Many indices require the metabolic rate to be assessed and then propose a time exposure limit or a work/rest cycle. However, the most common adaptations to working in hot environments are behavioral ones: reduction of the work rate (and thus of the considerable metabolic heat generated)^(10–12) and removal of clothing. Parsons⁽¹³⁾ noted that the realistic accuracy in estimating metabolic rate is only ± 50 percent. Job tasks are also becoming more varied due to increasing mechanization and “multi-skilling” of the workforce. Combined with the trend toward longer working hours (e.g., 12-hour shifts), it is common for work rates to vary significantly during a shift, and for workers to move frequently from one location to another (with potentially very different levels of thermal stress). It could therefore be argued that indices that require estimation of metabolic rates from observations are not very practical and are prone to considerable error.
- Some indices do not explicitly take wind speed over the skin into account. This includes the widely used WBGT (wet bulb globe temperature), originally developed as a proxy for the corrected effective temperature (CET). WBGT uses the natural wet bulb temperature, which is relatively insensitive to wind speed; however, CET, from which WBGT was derived, is quite sensitive to wind speed. In addition, the natural wet bulb used to calculate WBGT is not generally shielded, so it will be insensitive to wind speed but quite sensitive to high radiant heat loads, such as solar radiation.

It is difficult to have a simple, practical measure of (heat) acclimatization. However, acclimatization is known to be an important adaptation to working in heat. A robust protocol needs to provide for this. Some protocols such as the American Conference of Governmental Industrial Hygienists (ACGIH[®]) threshold limit value (TLV[®])⁽¹⁴⁾ (using WBGT) have adopted various corrections in an attempt to take acclimatization into account; however, many indices do not provide advice for both acclimatized and unacclimatized states.

Other problems exist with rational indices such as ISO 7933,⁽¹⁵⁾ especially when applied to hot, humid environments with low wind speeds. These problems include:

- An adjustment is frequently made within the index formulation to increase the relative wind speed (between body surface and the air) when the actual wind speed

is low. This is justified, firstly, on the basis of step test experiments, which indicate that at low wind speeds, an artificial air movement is induced over the skin by virtue of the work rate of the body, including arms and legs. This is not always the case, for example, in underground mines, where the metabolic work is sometimes produced by arm or upper body movements alone (not whole body) or is sometimes done against gravity. In these cases, work can be mainly isometric muscle contraction. When under extreme thermal stress, static muscle work can be as demanding as dynamic muscle work but may produce little induced air movement over the skin. From the authors' observations of self-paced workers in thermally stressful situations, it is not valid and may even be dangerous to justify an increased relative wind speed on this basis. Secondly, it is based on the minimum convection currents that are set up between a “hot” body and the fluid environment (in this case the ambient air) around that body. This is an acceptable use of minimum wind speeds and is supported by many authors. Refer to literature reviews by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE)⁽¹⁶⁾ and Hólmer.⁽¹⁷⁾

- The assumption that the intrinsic clothing insulation (I_{cl}) and vapour permeation efficiency (i_{cl}) of the clothing ensemble do not change as thermal conditions change. Clearly, under thermal stress, workers sweat profusely and their clothing becomes saturated. This reduces the intrinsic clothing insulation, as most of the thermal resistance to dry heat in clothing comes from the air trapped between the clothing and the skin, and within the cloth fibers. The thermal conductivity of water is 20 times that of air, which largely accounts for the reduction in insulation of wet clothes. Some of these problems have been recognized and are currently being addressed in the European research project on heat stress and the proposal for revision of ISO 7933.^(6,7,17)
- The absence of a fluid replacement term in the ISO protocol is a weakness. ISO assumes that fluid replacement will not match sweat loss during the working shift, probably because this phenomenon of “voluntary dehydration” has been reported by many authors.^(18,19) However, workplaces have been observed where workers are careful to replace the fluids they are losing⁽²⁰⁾ and do not build up a water deficit.
- The ISO model is based on an overall “average” thermal strain value for a shift, even when different stress conditions exist during the shift. This is a problem as it does not use the “ending” values from one work segment as the “starting” values for the next or check that limiting physiological criteria are not exceeded during each segment. Averaging values over a shift may or may not be a weakness in practice, but is inconsistent in a protocol that is intended to provide advice on either external

pacing (mandatory work/rest cycles) or the duration of exposure, and which simultaneously sets up limits in terms of heat storage (deep body core temperature) and sweat rate.

The thermal work limit algorithm builds on work originated by Mitchell and Whillier,⁽²¹⁾ who developed an index "specific cooling power," which subsequently became known as "air cooling power" (ACP). The original formulation of ACP used a fixed mean skin temperature. Stewart and Van Rensburg⁽²²⁾ then proposed a method involving variable mean skin temperatures, but did not consider the effects of clothing. McPherson⁽²³⁾ later proposed a more general formulation for a range of thermal environments, including comfort and limiting conditions, but used limiting values that were relevant to hot, humid conditions.

With its units of watts per square meter and its measurement of maximum sustainable metabolic rate, TWL is a convenient measure for both occupational health practitioners and environmental engineers, as it allows direct comparison between limiting metabolic rates and environmental conditions. This allows the impact of engineering controls and other interventions (e.g., changed clothing) to be assessed directly. This article describes the formulation of TWL and the resulting limits and interventions and shows how the index can be extended to unacclimatized workers.

METHODS

The basic purpose of the thermal work limit index is to calculate the maximum metabolic rate, in watts of metabolic heat per square meter of body surface area, that can be continuously expended in a particular thermal environment, while remaining within safe physiological limits. With TWL, the higher the number, the higher the sustainable work rate (in terms of thermal stress). The foundation of the TWL algorithm is derived from the work discussed below.

Wyndham⁽²⁴⁾ conducted a number of experiments measuring physiological conductance (the blood-borne flow of heat to the skin) along with steady-state deep body core and mean skin temperatures for a range of environmental conditions and metabolic rates. Complex equations were developed for these relationships. Later, Cabanac⁽²⁵⁾ reported that physiological conductance is a function of the thermoregulatory signal, defined as the weighted average of the deep body core and mean skin temperatures where the deep body core temperature is weighted at 90 percent and the mean skin temperature is weighted at 10 percent. Wyndham's original data plotted against the thermoregulatory signal is shown in Figure 1.

The limiting deep body core temperature in the standard TWL formulation is 38.2°C, although this is adjustable. The acceptable range for the thermoregulatory signal in the model is from 36°C to 39.5°C, based on Wyndham's experimental data.⁽²⁴⁾ For heat to flow from the deep body core to the skin, the maximum mean skin temperature cannot exceed the deep body core temperature, and in practice is usually more than 1°C cooler than

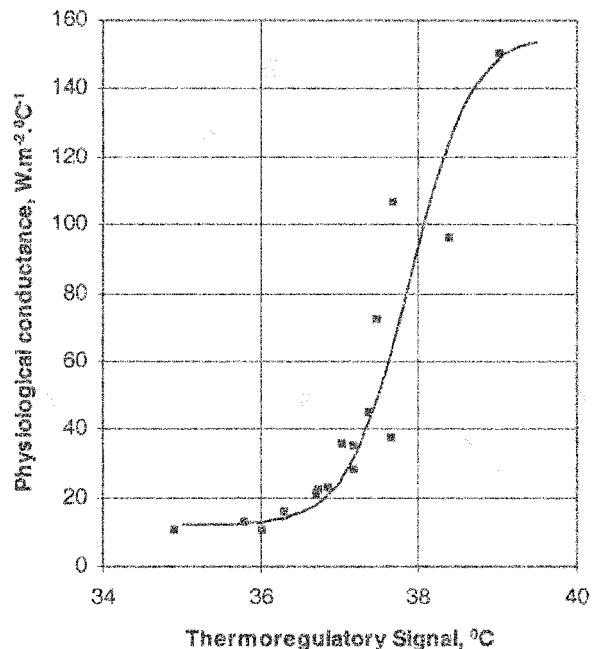


FIGURE 1
Relationship between physiological conductance (blood-borne heat transfer) from deep body core to skin and thermoregulatory signal, t_{Σ} , where $t_{\Sigma} = 0.1t_{\text{skin}} + 0.9t_{\text{core}}$ ⁽²⁴⁾ (data from Wyndham).

the deep body core temperature. This is true even under light work when higher skin temperatures may still be sufficient to remove the relatively low levels of metabolic heat. Continuous heavy work requires a larger gap between deep body core and mean skin temperatures for the larger amount of heat generated to flow from core to skin.⁽²⁴⁾

Wyndham⁽²⁴⁾ also measured sweat rates, plotted in Figure 2, against the same thermoregulatory signal. In the standard TWL formulation, maximum sweat rate (which is adjustable) is restricted to $0.67 \text{ kg/m}^{-2}/\text{hr}^{-1}$ (1.2 liters per hour for a standard person), which is within the steep (responsive) region of the sweat rate curve. It is well within reported sustainable limits of about $0.83 \text{ kg/m}^{-2}/\text{hr}^{-1}$ (1.5 liters per hour) noted for acclimatized workers by Taylor,⁽²⁶⁾ and is also close to the original P4SR limit of 4.5 liters over four hours recommended by McArdle.⁽²⁷⁾ The corresponding ISO 7933 sweat rate limit is 1.04 liters per hour, although ISO 9886⁽²⁸⁾ comments that the 1.04 liter per hour limit in ISO 7933 "must be considered not as (a) maximum value but as (a) minimal value that can be exceeded by most subjects in good physical condition."

Following from the definition of the psychrometric dew point temperature (the temperature at which moisture condenses from the air), the minimum possible mean skin temperature cannot be lower than the ambient dew point temperature if evaporation from the skin to the ambient environment is to occur. It is also necessary to establish the proportion of the sweat produced that actually results in evaporation and cooling.

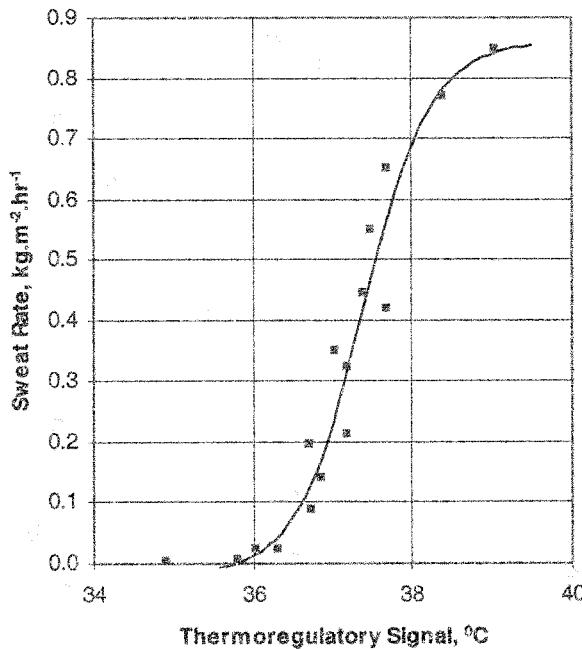


FIGURE 2

Relationship between sweat rate and thermoregulatory signal, t_{Σ} , where $t_{\Sigma} = 0.1t_{\text{skin}} + 0.9t_{\text{core}}$ (data from Wyndham).⁽²⁴⁾

The evaporation rate from the skin clearly cannot exceed that of a fully wet body in the same circumstances. However, even when the skin is only partly wet, not all the sweat produced is evaporated. This is because dripping commences well before the skin is fully wet, and the onset of dripping has been shown to be a function of the evaporative ability of the environment (Figure 3). This figure (redrawn from Stewart⁽³⁴⁾) shows experimental data derived by Galimidi and Stewart⁽²⁹⁾ along with the original theoretical curve for skin wettedness derived by Kerslake.⁽³⁰⁾ In this figure:

- λ is the latent heat of evaporation of sweat (kJ/kg^{-1}) and S_r is the sweat rate ($\text{kg/hr}^{-1}/\text{m}^{-2}$); therefore λS_r is the sweat rate using the units of W/m^{-2} (after conversion of hours to seconds).
- E is the actual evaporation rate of sweat (W/m^{-2}) under these conditions and E_{\max} is the maximum possible evaporation rate (W/m^{-2}) from a fully wet skin under these conditions.
- The Y-axis ($E/\lambda S_r$) is the ratio of the actual evaporation rate to the actual sweat rate and is a measure of the efficiency of sweating as a cooling mechanism in this condition; the maximum Y value is 1.0, at which point all the sweat produced is being evaporated.
- The X-axis ($\lambda S_r/E_{\max}$) is the ratio of the actual sweat rate to the maximum possible evaporation rate from a fully wet skin in this environment, and is therefore a measure of the capacity of the environment to evaporate

the sweat produced; where x-values exceed 1.0, sweat rates exceed the maximum possible evaporation rate in this environment.

- The product of any particular x-value and y-value on the solid line of this curve is $E/\lambda S_r \times (\lambda S_r/E_{\max}) = E/E_{\max} = w$ (defined as the *skin wettedness*). Skin wettedness values greater than unity are not possible.

Galimidi and Stewart⁽²⁹⁾ and Kerslake⁽³⁰⁾ identified two reasons why sweat drips from the body before the skin is fully wet. Firstly, the evaporative heat transfer coefficient varies over the body, so that areas with low coefficients are unable to evaporate all the sweat being produced and start to drip, while areas with high coefficients are still able to evaporate all the sweat produced. Secondly, some regions of the skin produce more sweat than others.

The experimental data in Figure 3 shows that a fully wet skin ($w = 1$) only occurs when the actual sweat rate is about 170 percent ($x\text{-value} = 1.7$, $y\text{-value} = 1/1.7 = 0.6$) of the maximum evaporation rate possible in the environment, at which point about 60 percent of the sweat is evaporating. It also shows that dripping of sweat from the skin starts when the skin surface is just under 50 percent wetted ($x\text{-value} = 0.46$ and $E/\lambda S_r$ falls below 1.0).

The efficiency of sweating therefore falls into three distinct zones:

- Zone A, where the evaporating ability of the environment is high, no sweat drips, the efficiency of sweating is therefore 100 percent, and the skin is not fully wet,

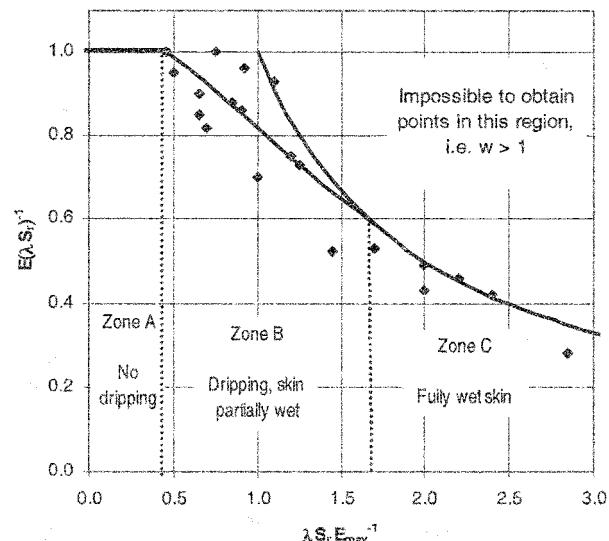


FIGURE 3
Comparison between predicted and observed relationships for evaporative cooling of an essentially nude male (redrawn from Stewart).⁽²⁸⁾

- Zone B, where dripping occurs but the skin is not fully wet, and
- Zone C, where the evaporating ability of the environment is low compared to the sweat rate, the skin is fully wet, and dripping occurs.

By deriving mathematical equations for these various relationships, and combining these with standard equations for heat exchange and psychrometric properties, including the influence of clothing, the maximum (limiting) metabolic rate to ensure a deep body core temperature and sweat rate remain within nominated safe upper limits can be calculated. These equations are detailed in Appendix 1.

The valid range for TWL is from resting (60 W/m^{-2}) to 380 W/m^{-2} , as this is the range of experimental data collected by Wyndham. TWL is not valid where the dew point temperature of the ambient air is above the skin or clothing temperature. Finally, as the equations used to derive the heat transfer through clothing are not valid for subjects in encapsulating protective clothing (EPC), TWL cannot be assumed to be valid where impermeable clothing is used.

DISCUSSION AND PRACTICAL APPLICATIONS

It is emphasized that the recommended values of TWL do not require constant assessment of metabolic rates in the workplace, which will vary considerably between workplaces and over the course of a work shift. This means that persons untrained in assessing metabolic rates can supervise the protocol. TWL is designed for workers who are well educated about working in heat, have control over their work rate, are healthy, and are well hydrated. Self-pacing works well when it is formally incorporated in a protocol where workers have the mandate to self-pace, and when supervisors and management are supportive.⁽⁵⁾

TWL suffers from the same problem as most other heat stress indices in that environmental conditions need to be measured to assess the required actions under the protocols. However, by using an index that is designed specifically for self-pacing, there is less emphasis needed on measuring environmental conditions, as workers are allowed to reduce their work rate as needed. In most circumstances, workers are not working near the maximum work rate for the particular environment and they recognize this themselves—no measurements are required. When they believe they are working close to one of the limits, measurements are taken. This has proved quite practical.

Recommended guidelines for TWL limits with the corresponding interventions are provided in Appendix 2. These are based on the hierarchy of safety controls, and include a range of engineering, procedural, and personal protective equipment (PPE) interventions.

While TWL does not require metabolic rates to be assessed for routine use, the index itself provides an estimate of the limiting metabolic rate from simple measurements of environmental conditions. Therefore, TWL is of benefit not only in assessing thermal stress directly, but also in allowing occupational

hygienists and engineers to make quantitative assessments of the following types of commonly encountered problems.

- The loss of productivity due to thermal stress. For example, if the metabolic rate (work rate) for a particular type of work in an environment of low thermal stress is 180 W/m^{-2} , and assuming a “resting” metabolic rate of 60 W/m^{-2} , then the productivity when working in an environment with a TWL of 120 W/m^{-2} is given by: Productivity = $(120-60)/(180-60) = 50\%$, where $(120-60)$ is the residual work capacity (the working rate less the resting rate) in this environment and $(180-60)$ is the residual work rate required for full productivity. Simple calculations of the cost of lost production and other economic impacts of environmental conditions can then be made.
- Using the same premises, work/rest cycles can be established.
- Indicative exposure times before reaching a limiting deep body core temperature can be estimated. Taking the above example, if work with an energy expenditure (metabolic rate) of 180 W/m^{-2} is required in an environment with a TWL of 120 W/m^{-2} , then the heat storage is 60 W/m^{-2} or 120 W , using a conservative surface area per person of 2 m^2 . If the typical worker has a mass of 80 kg , then the deep body core temperature will rise by about $60/3,500 \times 3,600/80 = 0.77^\circ\text{C}$ per hour, since the specific heat of the body is $3,500 \text{ J/(kg/K)}^{-1}$. If the maximum acceptable deep body core temperature is (say) 38.2°C and work starts from a cool condition (deep body core temperature 37°C), then withdrawal would need to occur no longer than $(38.2 - 37.0)/0.77 = 1.5$ hours after work in these conditions commences. Clearly this calculation would only be a starting point and field checks would be needed to confirm practical exposure times.
- The cost benefit of installing cooling installations can be assessed. Because TWL is measured in W/m^{-2} , it can easily be compared to watts of refrigeration. The impact of localized cooling using various types of refrigeration can therefore be measured directly. For example, consider a workplace being ventilated with $10 \text{ m}^3/\text{s}^{-1}$ of air at 30°C WB, 40°C DB, 40°C Globe, 100 kPa barometric pressure, and a wind speed of 0.2 m/s^{-1} . The initial TWL (with $I_{cl} = 0.35$ and $i_{cl} = 0.45$) is 110 W/m^{-2} (withdrawal conditions for self-paced work, refer to Appendix 2). Local refrigeration of 100 kW(R) (kilowatts of refrigeration effect) is installed. Standard psychrometric equations can be used to calculate that temperatures in the workplace will drop to 28.0°C WB and 31.4°C DB, which results in an increase in TWL to 158 W/m^{-2} . For conditions to be made acceptable for solitary, self-pacing, unacclimatized workers, the TWL would need to be improved

TABLE I
TWL values at various environmental conditions and clothing ensembles

MRT = DB + 2°C							MRT = DB							MRT = DB + 3°C							
Wind speed = 0.2 m/s ⁻¹							Wind speed = 0.5 m/s ⁻¹							Wind speed = 1.5 m/s ⁻¹							
Barometric pressure = 101 kPa							Barometric pressure = 115 kPa							Barometric pressure = 80 kPa							
$I_{cl} = 0.45, i_{cl} = 0.45$							$I_{cl} = 0.69, i_{cl} = 0.4$							$I_{cl} = 0.35, i_{cl} = 0.45$							
WB							WB							WB							
DB	24	26	28	30	32	DB	24	26	28	30	32	DB	24	26	28	30	32	DB	24	26	28
34	175	157	136	114	n/p	34	181	161	140	118	n/p	34	288	260	229	193	154	34	288	260	229
36	170	151	131	109	n/p	36	176	156	136	113	n/p	36	282	254	222	187	148	36	282	254	222
38	164	145	125	103	n/p	38	171	152	131	109	n/p	38	276	248	216	181	141	38	276	248	216
40	158	140	120	n/p	n/p	40	166	147	126	104	n/p	40	270	242	210	174	135	40	270	242	210
42	152	134	114	n/p	n/p	42	161	142	122	n/p	n/p	42	264	235	203	167	128	42	264	235	203

MRT = mean radiant temperature, °C; DB = dry bulb temperature, °C; WB = wet bulb temperature, °C; I_{cl} = intrinsic clothing thermal resistance, clo; i_{cl} = clothing vapor permeation efficiency, dimensionless; n/p = heat stress too extreme even for (continuous) light work. Permit required.

further to 220 W/m⁻² (refer to Appendix 2). The capital and operating costs of this engineering intervention (refrigeration) can be directly evaluated against the cost benefit of improved productivity.

- The “free” cooling available as a result of increased local air flow. Using the above example, the TWL could have been increased to the same 158 W/m⁻² by increasing the wind speed over the skin from 0.2 to 0.7 m/s⁻¹ without any addition of refrigeration. For indoor work, this could probably be achieved by installation of a local electric or compressed air-operated fan or venturi air mover. This is not to say that increasing the wind speed over the skin is able to increase the TWL in all situations; typically, increasing the wind speed beyond 4 m/s⁻¹ provides little further benefit.
- The serious and generally detrimental impact of clothing ensemble (clothing plus any additional PPE) on thermal stress, and particularly any loss of vapor permeability; when various hazards in the workplace are being evaluated and PPE or alternative protective clothing ensembles is a consideration, the effects on thermal stress of the proposed changes can therefore be easily evaluated by adjusting the I_{cl} and i_{cl} values.

Table I shows typical TWLs over a range of conditions. In the past, it has not been practical to routinely measure the five environmental parameters required to evaluate TWL for each workplace each shift. This is one of the reasons why empirical indices such as WBGT have been popular—the technology has not been available to support more elaborate indices. However, a suitable pocket-sized instrument is now available⁽³²⁾ with the necessary accuracy to measure the parameters and with an internal processor to perform the necessary calculations for the heat strain model.

CONCLUSIONS

Thermal work limit has advantages over other available indices where well-informed workers are undertaking self-paced work. The index can also be used, where paced work is unavoidable, to give realistic pacing guidelines (work/rest schedules) and can be used to trigger a formal permitting system. Practical intervention levels and protocols have been developed to assist in the reduction of heat illness. These have been extended to take into account unacclimatized workers. TWL also allows cost calculations to be undertaken into lost productivity and the impact of possible engineering remedies to be evaluated directly. A method for calculating TWL is proposed, which integrates data and theory published elsewhere, but which has been extensively tested in several hot industrial workplaces inside the tropics. TWL should only be used within the environmental conditions for which this data is valid (metabolic rates from 60 W/m⁻² to about 380 W/m⁻²).

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APPENDIX 1 DERIVATION OF TWL

Unless otherwise noted, in this appendix all references to ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) are to the reference text: 1997 *Fundamentals* SI edition, chapter 8, Thermal Comfort.⁽¹⁶⁾ All references to EESAM are to: *Environmental Engineering in South African Mines*, 1989, chapter 20, Fundamentals of Human Heat Stress.⁽³⁴⁾ All temperatures are degrees Celsius.

In the TWL protocol, formulas for convection, radiation, and evaporation were derived from Stewart,^(22,33,34) who derived

them from Mitchell and Whillier's⁽²¹⁾ work. Mitchell took "about a thousand measurements of each of radiation and convection ... spanning the complete range of temperature, wind speed, and humidity experienced underground." Mitchell's values were all derived from mine workers in a climate laboratory wearing shorts only. Formulas for clothing correction are derived from ASHRAE.

The experimental data collected by Wyndham⁽²⁴⁾ has a range from resting (60 W/m^{-2}) to about 380 W/m^{-2} . These rates were sustained over three consecutive hours. The typical aerobic capacity ($\dot{V}O_{2\max}$) of modern industrial workers is 30 to 50 $\text{ml/kg}^{-1}/\text{min}^{-1}$. Assuming a sustainable rate without fatigue at 33% of $\dot{V}O_{2\max}$, this corresponds to a metabolic rate of 130 to 215 W/m^{-2} for a standard person (70 kg, 1.8 m^2). Given that TWL is defined as the sustainable metabolic rate under limiting conditions, the primary range of interest is, therefore, from light work (100 W/m^{-2}) to about 215 W/m^{-2} , although the experimental data is valid from 60 to 380 W/m^{-2} .

Ignoring heat loss via conduction (which is only significant for a worker in contact with a hot surface such as hot solids or liquids), the heat balance equation for humans and other homeotherms is as follows:

$$M - W = C + R + E + B + S_{sk} + S_c \quad [\text{ASHRAE Eq. 1}]$$

Where W = rate of mechanical work accomplished

C = rate of heat loss from skin due to convection

R = rate of heat loss from skin due to radiation

E = rate of total evaporative heat loss from the skin

B = rate of convective and evaporative heat loss from respiration

S_{sk} = rate of heat storage in skin compartment

S_c = rate of heat storage in deep body core compartment

Note that the units for each term are W/m^{-2} .

By definition, for steady-state conditions, both S terms must be zero.

As the maximum useful mechanical work done by a human is of the order of 20 to 24 percent of the metabolic rate and is often zero in occupational settings, the W term is usually assumed to be zero, which is generally a conservative position to adopt. Note, however, that where negative work is done (i.e., work is done on the human body by an outside force, for example, a worker lowering a heavy object against gravity), the W term becomes negative and adds to the metabolic heat that must be dissipated by the body. Therefore, assuming W to be zero is not the "worst case" scenario in all circumstances.

Heat losses due to respiration are given by the following formula:

$$B = 0.0014 M (34 - t_a) + 0.0173 M (5.87 - p_a) \quad [\text{ASHRAE Eq. 26}]$$

where t_a = dry bulb temperature of ambient air in degrees C

p_a = partial water vapor pressure in ambient air in kPa

Note that in all ambient environmental conditions (except the extreme cold), air leaves the lungs in a saturated condition. For ambient dry bulb temperatures in the 30°C to 45°C range and ambient humidity in the 40 to 100 percent range, the range of heat losses due to breathing is 2 to 10 W/m^{-2} .

Losses from radiation for an essentially nude person can be given by the following relationship:

$$R = h_r f_r (t_{skin} - t_{rad}) \text{ in } \text{W/m}^{-2} \quad [\text{EESAM Eq. 8}]$$

where

$$h_r = 4.61 [1 + (t_{rad} + t_{skin})/546]^3, \text{ W/m}^2/\text{K}^{-1} \quad [\text{EESAM Eq. 9}]$$

f_r = posture factor (dimensionless), typically 0.73
for a standing person (ASHRAE Eq. 35).

t_{rad} = mean radiant temperature in degrees C

The radiant heat transfer coefficient, h_r , is a function of the difference in mean skin and mean radiant temperatures. As the difference between these two temperatures is generally small, the variation in h_r is also generally small. For example, over the range of dry bulb and globe temperatures from 22°C to 34°C and wind speeds from 0 to 4 m/s^{-1} (t_{rad} is a function of both globe temperature and wind speed), h_r varies within the small range of 5 to $6 \text{ W/(m}^2/\text{C})^{-1}$, which is in accordance with *ASHRAE 1997 Fundamentals*, Chapter 8, Eq. 35.

Losses from convection for an essentially nude person can be given by the following relationship:

$$C = h_c (t_{skin} - t_a) \text{ in } \text{W/m}^{-2} \quad [\text{EESAM Eq. 11}]$$

where

$$h_c = 0.608 P^{0.6} V^{0.6}, \text{ W/m}^2/\text{K}^{-1} \quad [\text{EESAM Eq. 13}]$$

where P = the ambient barometric pressure in kPa

V = the wind speed over the skin in m/s^{-1}

In the TWL formulation, wind speed has a minimum value of 0.2 m/s^{-1} , which is about the minimum ("natural") convection current between a hot body and surrounding air (*ASHRAE 1997 Fundamentals*, Chapter 8, Table VI). Under TWL, wind speed is also limited to 4 m/s^{-1} . While a wind speed greater than 4 m/s^{-1} does have some further minor impact on convection and evaporation, it also tends to lift dust and other particles off surfaces, which can create separate hygiene problems.

The convective heat transfer coefficient, h_c , is a function of barometric pressure and wind speed only, not of temperatures. Over the range of wind speeds from 0 to 4 m/s^{-1} , h_c varies from 3.7 to $22 \text{ W/(m}^2/\text{C})^{-1}$. For low wind speeds, the resulting values of h_c are very similar to those from ASHRAE Table VI, last equation, but do become more conservative compared to ASHRAE at higher wind speeds.

These formulations of h_c assume a reasonably uniform skin temperature. This will be true when the subject is working at the limiting condition, but will not be true for submaximal work in cool conditions, where the skin temperature of the extremities

is typically much cooler than that of the trunk. As TWL is at the limiting condition, an assumption of uniform skin temperature is reasonable.

Clothing affects the sensible ($C + R$) and evaporative (E) heat losses. Sensible heat losses can be corrected using the process outlined in *ASHRAE 1997 Fundamentals*, Chapter 8.

$$h = h_r + h_c \text{ in } W/(m^2/K)^{-1}$$

[ASHRAE Eq. 9]

$$f_{cl} = 1.0 + 0.3 I_{cl}, \text{ dimensionless}$$

[ASHRAE Eq. 47]

$$t_{oper} = (h_r t_{rad} + h_c t_a) / (h_r + h_c) \text{ in degrees C}$$

[ASHRAE Eq. 8]

where t_{oper} = the operative temperature

$$R_{cl} = 0.155 I_{cl} \text{ in } (m^2/K)/W^{-1}$$

[ASHRAE Eq. 41]

where I_{cl} is the intrinsic clothing thermal resistance in clo units. Do not confuse I_{cl} with i_{cl} , the clothing vapor permeation efficiency (refer later). Despite the potential confusion, these are the most commonly accepted abbreviations for these quite different parameters (ASHRAE).

$$F_{cle} = f_{cl} / (1 + f_{cl} h R_{cl}), \text{ dimensionless}$$

ASHRAE Table II *Sensible Heat Flow* last equation

$$C + R = F_{cle} h (t_{skin} - t_{oper})$$

ASHRAE Table III *Sensible Heat Loss* third equation

Note that for a nude body, $I_{cl} = 0$ and hence $F_{cle} = 1$, resulting in $C + R = h(t_{skin} - t_{oper})$.

There is a complex and generally inadequately understood interaction between clothing ventilation, wind penetration, moisture content, the “pumping action” due to physical work (itself partly dependent on the nature of the work and the body parts in motion), and the thermal insulation of clothing ensembles, among other factors. Real data is best obtained by the use of sweating, moving mannequins, and these are rare. Further experimental and theoretical work is currently being conducted (e.g., the European research project on heat stress and the proposal for revision of ISO 7934^(6,7,17)) to better establish the impact of wetness and wind speed on dry and evaporative heat losses. These revised approaches can be incorporated into TWL as consensus develops in these areas. Note, however, that the use of a highly sophisticated clothing model may result in a complicated and poorly understood heat stress index that may be prone to misinterpretation and error.

The evaporative heat transfer coefficient for an essentially nude person, $h_e(W/m^2/K^{-1})$, is given by the following relationship:

$$h_e = 1587 h_c P / (P - p_a)^2$$

[EESAM Eq. 17]

where P and p_a are the barometric and water vapor pressure in the ambient air, respectively, in kPa. Note that, since p_a is much less than P , and P is approximately equal to 100, this formula is almost identical to ASHRAE equation 27, i.e., $h_e = 16.5 h_c$. It

can further be seen that in typical conditions, h_e will be about 16 times the value of h_c , which in turn is 3 to 6 times the value of h_r , illustrating the point that evaporative heat transfer is the main mechanism for heat loss when under thermal stress.

Adjustments to allow for clothing can follow the ASHRAE approach:

$$R_{cl} = R_{cl} / (LR i_{cl}), \text{ dimensionless}$$

ASHRAE Table II *Parameters Relating Sensible and Evaporative Heat Flows*, first equation

where i_{cl} is the “clothing vapor permeation efficiency, the ratio of the actual evaporative heat flow capability through the clothing to the sensible heat flow capability as compared to the Lewis Ratio” (ASHRAE Table I text). For dry indoor clothing, i_{cl} is typically about 0.35 to 0.45 (ASHRAE Table VII), while for light cotton clothing with reasonable wicking properties, may be higher but cannot exceed 1.0 (the value if evaporative heat transfer through the clothing is unimpeded). LR is the Lewis Ratio and for typical conditions has the value of 16.5 (ASHRAE equation 27).

$$F_{pcl} = 1 / (1 + f_{cl} h_e R_{cl}), \text{ dimensionless}$$

ASHRAE Table II *Evaporative Heat Flow*, last equation

where F_{pcl} is the “permeation efficiency, the ratio of the actual evaporative heat loss to that of a nude body at the same conditions, including an adjustment for the increase in surface area due to clothing” (ASHRAE Table I text).

The actual heat transfer from the evaporation of sweat off the skin, $E_{sk}(W/m^2)$, is:

$$E_{sk} = w F_{pcl} f_{cl} h_e (p_s - p_a)$$

ASHRAE Table III *Evaporative Heat Loss*, third equation

where p_s = saturated water vapor pressure at the mean skin temperature in kPa, and
 w = skin wettedness

The maximum possible value of $E_{sk}(E_{max})$ is when the skin is fully wet ($w = 1$). Fully wet skin is not possible for a full work shift; however, healthy acclimatized individuals can maintain fully wet skin for several hours. In the context of self-paced work where workers can withdraw when stressed and who take a meal break approximately every four hours, the assumption of fully wet skin is a reasonable maximum value for the design of a limiting (maximum) allowable level. It is also the limit adopted by ISO for acclimatized persons.

Note that for a nude body $I_{cl} = 0$, hence $R_{cl} = 0$ and $R_{cl} = 0$. Thus, as expected, the vapor permeation efficiency, i_{cl} , becomes increasingly less significant as fewer clothes are worn. Further, for a nude body, $F_{pcl} = 1$ and $E_{sk} = wh_e(p_s - p_a)$.

The heat transfer from the deep body core to the skin, $H(W/m^2)$, must equal the heat losses from the skin to the ambient environment via radiation, conduction, and evaporation. This “core-to-skin” transfer can be expressed as:

$$H = K_{cs}(t_{core} - t_{skin})$$

[EESAM Eq. 23]

where K_{cs} is the physiological conductance from deep body core to skin, in $\text{W}/(\text{m}^2/\text{K})^{-1}$.

This requires the physiological conductance, K_{cs} , to be determined. K_{cs} is a function of both deep body core and mean skin temperatures as shown in Figure 1 where the thermoregulatory signal, t_Σ , is given by:

$$t_\Sigma = 0.1 t_{\text{skin}} + 0.9 t_{\text{core}} \quad \text{Cabanac}^{(25)}$$

The physiological conductance, K_{cs} ($\text{W}/\text{m}^{-2}/\text{K}^{-1}$), can then be satisfactorily described by:

$$K_{cs} = 84 + 72 \tanh[1.3(t_\Sigma - 37.9)] \quad \text{curve fitted to Figure 1}$$

where \tanh is the hyperbolic tan value.

Sweat rate, S_r ($\text{kg}/\text{m}^{-2}/\text{hr}^{-1}$), is also a function of the thermoregulatory signal as shown in Figure 2. This curve can be adequately described by:

$$S_r = 0.42 + 0.44 \tanh[1.16(t_\Sigma - 37.4)] \quad \text{curve fitted to Figure 2}$$

The latent heat of evaporation of sweat, λ , is given by:

$$\lambda = 2430 \text{ kJ/kg}^{-1} @ 30^\circ\text{C} \quad [\text{ASHRAE Eq. 14}]$$

From Figure 3, the actual evaporation rate, E , in W/m^{-2} , is given by:

$$\begin{aligned} \text{For } \lambda S_r / E_{\max} < 0.46 & \quad E = \lambda S_r \\ \text{For } 0.46 \leq \lambda S_r / E_{\max} \leq 1.7 & \quad E = \lambda S_r \exp[-0.4127 \\ & \quad \times (1.8 \lambda S_r / E_{\max} - 0.46)^{1.168}] \\ \text{For } \lambda S_r / E_{\max} > 1.7 & \quad E = E_{\max} \end{aligned}$$

For a heat balance in the body,

$$H = E_{sk} \text{ (heat flow core to skin equals heat flow skin to environment), and}$$

$M = H + B$ (metabolic heat production equals heat flow core to skin + heat flow via respiration) The thermal work limit (TWL) for a person in this environment is then given by:

$$\text{TWL} = M$$

In summary, the above equations provide the heat flow from "skin to environment" due to convection, radiation, and respiration, skin wettedness, maximum evaporation rate and efficiency of sweating, heat flow from "core to skin," heat flow due to respiration, and sweat rate. There will then be a unique mean skin temperature and metabolic rate that provides a heat balance. This can be solved by iteration, at which point the body is in thermal equilibrium with the environment.

TABLE II
Recommended TWL limits and interventions for self-paced work

TWL limit (W/m^{-2})	Name of limit/zone	Interventions
<115 (or DB > 44°C or WB > 32°C)	Withdrawal	<ul style="list-style-type: none"> No ordinary work allowed Work only allowed in a safety emergency or to rectify environmental conditions Permit to work in heat must be completed and authorized by manager beforehand Dehydration test at end of shift Personal water bottle (4-liter capacity) must be on the job at all times
115 to 140	Buffer	<ul style="list-style-type: none"> Rectify ventilation or redeploy workers if possible No person to work alone No unacclimatized person to work If work does continue, a corrective action request must be completed and signed by the manager within 48 hrs Wind speed must be increased to at least 0.5 m/s^{-1} Dehydration test at end of shift Personal water bottle (4-liter capacity) must be on the job at all times
140 to 220	Acclimatization	<ul style="list-style-type: none"> Acclimatized persons allowed to work, but not alone Personal water bottle (4-liter capacity) must be on the job at all times
>220	Unrestricted	<ul style="list-style-type: none"> No limits on work due to thermal stress

The resulting interactive desktop version of the TWL model, developed in Microsoft Excel using Visual Basic for Applications, is available from the authors at mvamail@tpg.com.au.

APPENDIX 2 RECOMMENDED GUIDELINES FOR TWL PROTOCOLS

Table II provides guidelines that have been introduced into several workforces with a large number of employees exposed to thermally stressful environments. Brake, Donoghue, and Bates⁽²⁾ and Donoghue, Sinclair, and Bates⁽³⁾ provided more details on some of these interventions, such as the health screen, acclimatization protocol, and dehydration tests.

The purpose of these protocols is primarily to ensure that management attention and progressively more serious intervention occurs at various threshold points.

The TWL value of 115 W/m⁻² for the “withdrawal” limit (the trigger limit beyond which persons are withdrawn from the environment) was selected because 115 W/m⁻² is an approximate metabolic rate for light work. When even light work is not continuously possible for acclimatized workers, they should be withdrawn for three reasons: 1) There is little practical benefit in keeping workers in such conditions, as productivity is excessively low; 2) if even light work is not continuously sustainable, a formal work-rest cycle should be initiated, and this probably requires supervision to positively ensure the employer’s “duty of care” is met; and 3) because productivity is so low, workers frequently become frustrated and there is a danger that they will not continue to self-pace, which could result in hyperthermia.

It is important to recognize that work can still be undertaken when the TWL is less than 115 W/m⁻², but it is not conducted on a self-paced, self-supervised basis; a formal permitting system with prior management approval is required. Because TWL is quite sensitive to wind speed, it is sometimes possible to improve the air flow over the skin and continue work (i.e., move out of the withdrawal zone) without changing the temperature or humidity.

Workers are also withdrawn (or subject to a permit system) whenever the dry bulb temperature exceeds 44°C, irrespective of the TWL, as this temperature is close to the skin temperature at which several authors have found exposed skin discomfort or burning to commence.^(13,17) Short exposures at ambient temperatures above 44°C can be tolerated, but continuous exposure to temperatures in excess of this is undesirable, especially under high wind speeds, where the insulation value of the air layer (the only protection for exposed skin) reduces to almost zero.

Workers are also withdrawn (or subject to a permit system) when the wet bulb temperature exceeds 32°C, irrespective of the TWL. This is because relatively small errors in measuring the individual environmental parameters can generate errors up to 20 W/m⁻² in the calculated limiting metabolic rate under certain conditions. This is not a problem for self-paced work in “cooler” conditions (e.g., 200 W/m⁻²), as there is considerable latitude for the work rate to be adjusted downward. However, in hot conditions (e.g., 120 W/m⁻²), the work pace may already be very slow and it would be difficult to adjust it downward any further without taking regular rest pauses. Clearly, a relative error of 20 W/m⁻² at a low TWL is much larger than at a high TWL, and the potential adverse consequences of the error are more severe. The additional limit of the wet bulb temperature was chosen because it has the strongest single influence on TWL and can be measured quite accurately. The wet bulb limit does not replace the TWL limit but adds a further “backstop” to the TWL values. The value of 32°C WB was chosen as it has historically been considered to be an upper limit for continuous light work.

The limit of 140 W/m⁻² for the “buffer” limit was selected for two reasons. Firstly, it is desirable to have a graded response to increasing levels of heat stress, to avoid workers working in “near-withdrawal” conditions for several consecutive shifts. The buffer limit does this by providing a zone of 25 W/m⁻² (about 1°C to 1.5°C Wet Bulb) up against the “withdrawal” limit. Unacclimatized workers are not allowed to work in the buffer zone. The acclimatization period lasts for the first 7 calendar days back at work after being away for more than 14 days. Also, by requiring a “Corrective Action Request” to be completed when work is carried out in buffer zone conditions, it ensures that environmental engineering defects are noted and generally corrected before conditions approach withdrawal. A system of written corrective action requests is crucial to ensure defects in the workplace environmental conditions are recognized and rectified promptly.

The limit of 220 W/m⁻² for the “acclimatization” limit was selected because virtually all of the approximately 130 cases of heat illness⁽³⁾ found during the summer of 1997/1998 in one large underground mining operation in the tropics, which comprised workers with a wide variation of heat exposure and acclimatization, occurred where the TWL was less than about 220 W/m⁻². This limit (typically 26°C WB, 35°C DB and globe, 0.5 m/s⁻¹ wind speed and 100 kPa, or 28.7°C WBGT) can be compared to the “safe” condition for unacclimatized workers in summer uniforms doing light work (27.0°C WBGT), as indicated in ACGIH guidelines.