

## IH for the CSP 8: Heat Stress Index

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### Abstract

As discussed in the sixth article of this series, *IH for the CSP 6: Wet Bulb Globe Temperature Index*, the WBGT method of assessing heat stress presented by the American Conference of Governmental Industrial Hygienists (ACGIH) is an excellent screening tool. Properly applied, it is protective of the health of nearly all fit employees exposed to conditions of heat stress. At times, however, a more powerful tool is required. This tool is the Heat Stress Index (HSI).

The HSI allows separate calculation of radiant, convective, and metabolic heat loads, information important in designing engineering controls. The method also provides a calculation of the heat lost by the body through the evaporation of perspiration. Where heat stress conditions are too severe to be withstood for extended periods, the HSI method allows calculation of the Allowable Exposure Time (AET).

### HSI

The heat stress index is given by,

$$\text{HSI} = 100 \frac{M + R + C}{E_{\text{MAX}}}, \quad 1$$

Where M is the metabolic heat rate; R is the radiant heat load; C is the convective heat load; and  $E_{\text{MAX}}$  is the maximum evaporative capacity. The numerator is often called the "total heat load." The HSI can be interpreted as the percent of the maximum evaporative capacity represented by the total heat load.

A word on notation, some authors will subtract the rate at which external work is done, H, from the metabolic rate to get the heat load and write,

$$\text{HSI} = 100 \frac{M - H + R + C}{E_{\text{MAX}}}.$$

While it is true that external work done is energy that will not add to the heat load, this is a very poor approach unless M has been determined by measuring the actual oxygen consumption. The process of turning chemical energy into a work output is very inefficient. While doing work, the metabolic rate increases by much more than the work output. You can't cool your body by doing work. If M is estimated by another method (such as described below) subtracting the external work rate will cause you to underestimate the heat stress.

Also equation 1 is sometimes written.

$$HSI = 100 \frac{M \pm R \pm C}{E_{MAX}},$$

It is written in this manner to remind the reader that while M and  $E_{MAX}$  always have positive values, but R and C are sometimes negative. In Physics, we use the notation  $A = B \pm C$  to mean that both  $A = B + C$  and  $A = B - C$  are solutions to a given problem. In this context in Industrial Hygiene it does not mean there is more than one possible value for the HSI.

The relative risk due to heat stress is shown for values of the HSI in the table below

HSI	Interpretation
<0	Heat is being lost by the body, risk of hypothermia (cold stress)
=0	No heat load, negligible perspiration
10 - 20	Mild to moderate heat stress, slight to significant deterioration of higher intellectual functions, especially diligence tasks
40 - 50	Severe heat strain, a threat to health of all but physically fit, acclimatized individuals
70 - 90	Very severe heat strain, only a small percentage of persons can withstand such conditions. Medical surveillance programs (buddy systems), water replenishment schedules, and feasible engineering controls should be employed.
> 100	The heat load exceeds the maximum evaporative capacity ( $M+R+C > E_{MAX}$ ). Body core temperature will rise with time, after the allowable exposure time, all persons will experience adverse health effects. If exposed to these conditions for an extended period of time, even the most physically fit person on Earth would eventually be killed.

### **M, the Metabolic Heat Load**

There are many methods to estimate the metabolic heat load. The most precise would probably be to measure the employee's oxygen consumption. Provided the employee does not enter into anaerobic respiration (anaerobic metabolism to physicians) the metabolic heat load will be approximately 5 kcal per liter of oxygen. Obviously, this method would not be practical for most workplaces.

As discussed in article 6 of this series, the ACGIH recommends qualitatively selecting a value for M from a table, and multiplying that value by the ratio of the employee's weight to that of Reference Man (154 lb or 70 kg). The approximation that the metabolic heat load will be proportional to weight will be accurate for many tasks, but not all. For example, if tasks largely involve

standing or walking without a load, the approximation will be very good. For tasks where a great deal of external work is done, such as lifting heavy objects, the metabolic heat load may be largely independent of the employee's weight.

The method for determining the metabolic heat load most often used in HSI calculations is described below. Earlier editions of the TLV booklet used this method as well.

One term is taken from each column in the table below. The three terms are added to give the total metabolic heat load. All values listed in the table are in kilocalories per minute (kcal/min). It should be noted, sometimes in the literature the notation Cal (with a capital) is used for kcal.

Basal	Position/Movement		Type of Work	
1.0	sitting	0.3	light hand work	0.4
	standing	0.6	heavy hand work	0.9
	walking	2.0 - 3.0	light work with one arm	1.0
		add 0.8 per yard rise/min	heavy work with one arm	1.7
			light work with two arms	1.5
			heavy work with two arms	2.5
			light work with the body	3.5
			moderate work with the body	5.0
			heavy work with the body	7.0
			very heavy work with the body	9.0

The first column is for basal metabolism. This is the energy required just to keep the body alive. There is only one choice for basal metabolism, 1.0 kcal/min.

Next, observe if the employee is standing, sitting, or walking. If the employee is walking, a range of values is given. The industrial hygienist must use professional judgment to estimate where in this range the observed behavior will lie.

If the employee is walking up-hill for an extended distance (not back and forth on a grade) an additional 0.8 kcal is added for every yard of rise. Suppose an employee were walking briskly up-hill, rising 10 yards in 20 minutes. The value 3.0 kcal/min might be chosen to add to the total metabolic rate. An additional term, x, where,

$$x = \frac{10 \text{ yard}}{20 \text{ min}} \frac{0.8 \text{ kcal}}{\text{yard}} = 0.4 \text{ kcal/min} ,$$

is added to the value chosen for walking metabolic rate, and 3.4 kcal/min (3.0 kcal/min + 0.4 kcal/min) is added to the total metabolic rate from the second

column. The value 0.8 kcal/yard can be **thought** of as a conversion factor for converting yards/min to kcal/min.

The entry from the third column is determined by observing, and characterizing, the work done. Hand work is work where the arms do not move significantly, such as typing or assembling small parts at a workbench. If the arms move significantly, but the shoulders remain stationary, the work is termed "arm work." Work with the body often involves lifting, pushing or pulling, such as during material handling or digging.

When work is not continuous, such as when a work/rest regime is in place, or the employee moves about the workplace performing different tasks, the time-weighted average should be used. The time-weighted average metabolic rate is given by,

$$M_{TWA} = \frac{M_1(t_1) + M_2(t_2) + \dots + M_n(t_n)}{t_1 + t_2 + \dots + t_n}, \quad 2$$

where  $M_i$  is the metabolic rate observed during time  $t_i$ . The metabolic rate should be averaged over the time during which other heat stress measurements were made.

It should be noted that in order to add or subtract, values must have the same units. In the discussions below,  $R$ ,  $C$ , and  $E_{MAX}$  will have the units of BTU/hr. In order to convert kcal/min to BTU/hr the following conversion factors are required.

$$\text{BTU} = 0.252 \text{ kcal}, \quad \text{and} \quad \text{hr} = 60 \text{ min} .$$

Therefore,

$$\text{kcal/min} = 238.1 \text{ BTU/hr} .$$

### **R, the Radiant Heat Load**

Every object at a temperature higher than absolute zero gives off electromagnetic radiation. We are all continually exchanging radiation with our environment. Electromagnetic radiation with frequencies in the near infrared band (i.e. with a frequency near to that of visible red light) is sensed as heat. Calculation of the radiant heat load requires the dry bulb temperature (temperature of a normal thermometer), the globe temperature (temperature inside a hollow black sphere), and the air velocity.

The normal skin surface temperature is 95 °F. If the effective radiative temperature of the surroundings is greater than 95 °F, the body absorbs more radiant energy than it gives off ( $R > 0$ ). If it is less than 95 °F the body gives off more than it absorbs ( $R < 0$ ). The effective radiative temperature of the

surroundings is called the "wall temperature,"  $T_w$ . If we were in a black box, with no other sources of radiation, the effective radiative temperature of the environment would equal the temperature of the walls. If there were no air in the environment, the wall temperature would equal the globe temperature. However, since the globe exchanges energy with the environment through contact with the air as well as by exchanging radiation, we must correct the globe temperature to account for heat lost to (or gained from) the air. The wall temperature,  $T_w$ , is given (in  $^{\circ}\text{F}$ ) by,

$$T_w = [ (GT+460)^4 + 1.03 \times 10^8 V^{0.5} (GT - DB) ]^{1/4} - 460 , \quad 3$$

Where  $GT$  is the globe temperature in  $^{\circ}\text{F}$ ,  $V$  is the air velocity in feet per minute (fpm), and  $DB$  is the dry bulb temperature in  $^{\circ}\text{F}$ . The value 460 is used to convert the globe temperature to an absolute scale,  $^{\circ}\text{R}$  (Rankin), and then to convert the wall temperature back to  $^{\circ}\text{F}$ .

The radiant heat load is then given by,

$$R = 17.5 \frac{\text{BTU}}{\text{hr}} (T_w - 95^{\circ}\text{F}) . \quad 4$$

Notice, if the wall temperature is greater than the skin surface temperature ( $95^{\circ}\text{F}$ ),  $R$  will have a positive value, i.e. the body is absorbing radiant energy from the environment. If  $T_w < 95^{\circ}\text{F}$ ,  $R$  is negative and radiative heat is lost to the environment. The value for  $R$  calculated above does not account for clothing that may be worn. In general light-colored clothing slows the exchange of radiant energy and should be worn in hot environments with a positive radiant heat load. Contrary to intuition, dark clothing should be worn in hot environments where the radiant heat load is negative.

### **C, the Convective Heat Load**

The convective heat load is energy exchanged with the environment due to a difference in temperature between the air around us and the surface of our skin. If the air were perfectly still, it would come to equilibrium with the skin surface and very little (but still some) energy would be exchanged. When any fluid (gas or liquid) flows over a solid surface, there is a "boundary layer" of fluid in laminar flow. The boundary layer acts as an insulator limiting heat exchange. The more rapid the fluid flow, the thinner the boundary layer becomes. Therefore, the convective heat load depends not only on the dry bulb temperature and the skin surface temperature, but also on the air velocity. The convective heat load is given by,

$$C = 0.756 \frac{\text{BTU}}{\text{hr}} (DB - 95^{\circ}\text{F}) V^{0.6} , \quad 5$$

where DB is the dry bulb temperature in °F and V is the air velocity in fpm. This equation only applies when V is significantly greater than zero.

### **$E_{MAX}$ , the Maximum Evaporative Capacity**

When the body has a positive heat load (i.e. when the energy lost to the environment is less than the metabolic heat load) the body will remove excess heat through the evaporation of perspiration. The maximum rate at which heat energy can be removed through evaporation of perspiration,  $E_{MAX}$ , is limited by the humidity already present in workplace air and the air velocity. If the air is already saturated with moisture (100% relative humidity) no evaporation can take place and  $E_{MAX} = 0$ . If the air is nearly stagnant, it cannot carry moisture away from the worker effectively. Some moisture will still leave the worker through diffusion, so  $E_{MAX}$  will be small, but not zero. The maximum rate at which the body can remove heat through perspiration,  $E_{MAX}$ , is given by,

$$E_{MAX} = 2.8 \frac{\text{BTU}}{\text{hr}} (42 \text{ mm Hg} - \text{PW}) V^{0.6} , \quad 6$$

where PW is the partial pressure of water in workplace air millimeters of mercury (mm Hg) and V is the air velocity in fpm. For the reason stated above, equation 6 cannot be used for very low air velocities. For the curious, the value 42 mm Hg is used because is the partial pressure of saturated (100% relative humidity) air at the skin surface temperature (95 °F). The partial pressure of water in air is determined by measuring the dry bulb temperature and the forced wet bulb temperature using the psychrometric charts as described in the previous article of this series, *IH for the CSP 7: Relative Humidity*.

There is one further limiting factor for  $E_{MAX}$ . Regardless of how dry the air is, or how fast it moves, the body can only secrete perspiration at a limited rate. Therefore  $E_{MAX}$  can never exceed 2400 BTU/hr.

### **AET, Allowable Exposure Time**

Whenever possible, processes should be engineered such that no employee is ever exposed to heat stress conditions with an HSI even near 100. When exposure to an HSI greater than 100 is unavoidable, only the fittest, acclimatized individuals should be permitted in those environments. Further, the time spent by each employee in such an environment must be strictly limited.

The absolute maximum time an individual should be in an environment with an HSI greater than 100 is called the allowable exposure time, AET. The AET must **not** be considered a safe duration of exposure. It is a period of time after which even the fittest employees are virtually certain suffer adverse health effects.

The AET is given by,

$$\text{AET} = \frac{250 \text{ BTU}}{M + R + C - E_{\text{MAX}}} \cdot 7$$

The denominator is the net rate at which the body is heating. The AET, therefore is a measure of how long it will take for the heat energy in the body to increase 250 BTU. This is the energy required to raise 154 lb of water 1.6 °F (0.9 °C). In other words, if an employee is exposed to heat stress for a time equal the AET, his/her body core temperature may increase on the order of 1.6 °F, about the physiological limit an individual can tolerate without adverse effect.