Chapter 5

Thermal Stress

Thermal stress can arise from exposures to either hot or cold environments. For a wide variety of work environments it is common for there to be extremes as well as wide fluctuations in the temperature; because of this, it is important to understand thermal stress. This chapter will focus on the factors and parameters that are used to characterize thermal stress, and, in addition, will discuss the effects that these conditions can produce on individuals who, in the normal course of their work, may be exposed to them.

RELEVANT DEFINITIONS

Thermal Stress

Heat Stress

Heat Stress is a condition that arises from a variety of factors among the most important of which are:

1. the ambient temperature,
2. the relative humidity,
3. the level of effort required by the job, and
4. the clothing being worn by an exposed individual.

An individual who is experiencing **Heat Stress** will tend to exhibit an array of measurable symptoms which can include some or all of the following:

1. an increased pulse rate,
2. a greater rate of perspiration, and
3. an increase in the individual's body temperature.

Heat Stress Disorders

The five physical disorders that can arise from heat stress, listed in increasing order of severity, are as follows:

1. Heat Rash: A heat rash — also often referred to as "prickly heat" — tends to arise in an individual after a period of prolonged sweating. It is characterized by an itchy reddening of the skin and a sudden decrease in the rate of perspiration.
2. Cramps: Heat cramps arise as a result of prolonged periods of a combination of sweating and a lack of fluid and salt intake. Such a situation causes an overall body electrolyte imbalance, and the primary symptomatic manifestation is severe muscle cramps, most frequently in the abdomen.
3. Dehydration: Dehydration is the result of excessive fluid loss. Among its most common causes are: excessive sweating, vomiting, diarrhea, and/or alcohol consumption. Symptoms of dehydration are often subtle but include exhaustion, overall weakness, dry mouth, decreased work output, etc.

4. Heat Exhaustion: Heat exhaustion arises from extreme cases of dehydration. It is characterized by some or all of the following conditions or symptoms: increasing pulse rate, decreasing blood pressure, slight to moderate increases in body temperature, fatigue, increasing levels of sweating, lack of skin color, dizziness, blurred vision, headache, decreased work output, and collapse.

5. Heat Stroke: Heat stroke is usually the result of very significant overexposure to the factors of heat stress. It can also arise from drug or alcohol abuse and on occasion from genetic factors. Heat stroke is almost always accompanied by an increase in body temperature to levels greater than 104°F (40°C). Symptomatic indications include: chills, irritability, hot & dry skin, convulsions, and unconsciousness.

Cold Stress

Cold Stress differs dramatically from Heat Stress. Typically a body will adapt to conditions of Heat Stress by increasing its level of perspiration in an effort to provide increased cooling. **Cold Stress** adaptations usually involve a decrease in the blood flow to the skin and the extremities. The principal causes of **Cold Stress** are exposure to cold temperatures and vibrations, either singly or in combination.

Cold Stress Disorders

The four physical disorders that can arise from cold stress, listed in increasing order of severity, are as follows:

1. Chilblains: Chilblains usually arise as a result of inadequate clothing during periods of exposure to cold temperatures and high relative humidities. Reddening of the skin accompanied by localized itching and swelling are the principal indications of chilblains.

2. Frostnip: Frostnip, which is similar to frostbite, results from prolonged, unprotected exposures to cold temperatures above 32°F (0°C). Symptoms of frostnip are areas of pain and/or itching, and a distinct whitening of the skin.

3. Frostbite: Frostbite is produced from unprotected exposures to cold temperatures at or below freezing — i.e., ≤ 32°F or 0°C. Frostbite is characterized by the sequential change in skin color from white to gray to black [depending upon the temperature and the length of exposure], a reduction in the sensations of touch ranging from slight to total [again depending upon the temperature and the length of exposure], and numbness.

4. Hypothermia: Hypothermia results from extreme exposures to the factors of cold stress, coupled possibly with dehydration and/or exhaustion. Alcohol and/or drug abuse can also contribute to hypothermia. A person who is experiencing hypothermia will usually show some or all of the following symptoms: chills, euphoria, pain in the extremities, slow and weak pulse, body temperature of less than 95°F (35°C), fatigue, drowsiness, and unconsciousness.

Ambient Conditions Related to Thermal Stress

Dry Bulb Temperature

The **Dry Bulb Temperature** is the most direct measurement of air temperature. By definition, it is to be accomplished by the use of a capillary thermometer that is completely exposed to and/or immersed in the air mass whose temperature is to be measured. This thermometer should be shielded from sources of radiant heat.

Wet Bulb Temperature

The **Wet Bulb Temperature** of an air mass differs from the Dry Bulb Temperature measurement by the fact that the fluid reservoir bulb of the capillary thermometer that is used to make this measurement is encased in a sheath of water moistened cloth. This wet sheath provides cooling to the thermometer bulb by the evaporation of water, in most cases causing the **Wet Bulb Temperature** to be less than its Dry Bulb Temperature counterpart — the obvious exception to this is the case where the ambient relative humidity is 100%, a condition wherein evaporation, and the resulting evaporative cooling, are effectively eliminated.

There are actually two categories of **Wet Bulb Temperature**. The first is the **Natural Wet Bulb Temperature** which is obtained simply by encasing a capillary thermometer bulb in a wet cloth and then using this combination to make an air temperature measurement. The other category is described as a **Psychrometric Wet Bulb Temperature**. **Psychrometric Wet Bulb Temperatures** are obtained by the use of a sling psychrometer, a tool that is made up of a pair of identical capillary thermometers, one of which is bare while the other is sheathed in a wet cloth. To obtain a reading from a sling psychrometer, this mechanism is whirled through the air, a process that produces a maximized rate of evaporative cooling for the wet bulb. The difference in the temperatures indicated by the two thermometers of a sling psychrometer can then be used to determine the relative humidity of the air mass being measured.

Air or Wind Speed

The **Air** or **Wind Speed** is simply the rate at which a mass of air is passing an arbitrary stationary point. The direction of movement is not important since this measure is used principally in a determination of the convective heat transfer to and from the air. It is typically measured by an anemometer.

Globe Temperature

The **Globe Temperature** of an air mass arises from the combination of heat input by radiation from the surroundings coupled with the simultaneous heat loss by the convective movement of air around the **Globe Temperature** measurement device, which is a 6-inch diameter, thin-walled copper, spherical globe, painted matte black with an appropriate temperature sensor at its center.

Effective Temperature

The **Effective Temperature** is an index that is used to relate the subjective effect that the thermal environment might be expected to have on the comfort of an individual who is exposed to that environment. It is a combination of the Dry Bulb, the Wet Bulb, and the Globe Temperatures.

Wet Bulb Globe Temperature Index

The **Wet Bulb Globe Temperature Index** [usually abbreviated, **WBGT**] is the most widely used algebraic approximation of an "Effective Temperature" currently in use today. It is an Index that can be determined quickly, requiring a minimum of effort and operator skill. As an approximation to an "effective temperature", the **WBGT** takes into account virtually all the commonly accepted mechanisms of heat transfer (i.e., radiant, evaporative, etc.). It does not account for the cooling effect of wind speed. Because of its simplicity, **WBGT** has been adopted by the American Conference of Government Hygienists (ACGIH) as its principal index for use in specifying a heat stress related Threshold Limit Value (**TLV**). For outdoor use (i.e., in sunshine), the **WBGT** is computed according to the following algebraic sum:

$$\mathbf{WBGT} = 0.7\,[NWB] + 0.2\,[GT] + 0.1\,[DB].$$

For indoor use, the **WBGT** is computed according to the following slightly modified algebraic sum:

$$\mathbf{WBGT} = 0.7\,[NWB] + 0.3\,[GT].$$

where:

where:	[NWB]	=	Natural Wet Bulb Temperature,
	[GT]	=	Globe Temperature, &
	[DB]	=	Dry Bulb Temperature.

RELEVANT FORMULAE & RELATIONSHIPS

Thermal Stress (Indoor/Outdoor), With & Without Solar Load

Equation #5-1:

Equation #**5-1** is the relationship that provides the **Wet Bulb Globe Temperature Index** [**WBGT**] that is applicable only to situations for which there is no solar load (i.e., no direct solar input to the condition or circumstance of the area or space being evaluated). Obviously, most indoor situations fulfill this requirement; in addition, any outdoor circumstance wherein the sun has been shaded — i.e., where it makes no radiant contribution to the thermal or temperature environment — also fulfills this condition. This category of the **Wet Bulb Globe Temperature Index** is usually identified with an "$_{\text{Inside}}$" subscript.

$$\mathbf{WBGT_{Inside} = 0.7[NWB] + 0.3[GT]}$$

Where:

- $\mathbf{WBGT_{Inside}}$ = the **Wet Bulb Globe Temperature Index**, applicable to any situation in which there is no Solar Load, usually measured in °C;
- **NWB** = the **Natural Wet-Bulb Temperature**, usually also measured in °C; however, it should be noted that any temperature scale may be used for these parameters, so long as the units of every temperature parameter in the formula are consistent with the units of every other temperature parameter; &
- **GT** = the **Globe Temperature**, also in units consistent with every other parameter in this formula.

Equation #5-2:

Equation #**5-2** is the alternative relationship that provides the **Wet Bulb Globe Temperature Index** [**WBGT**] that is applicable to situations for which there is a measurable solar load. Outdoor conditions usually require this approach; and, correspondingly, this category of the **Wet Bulb Globe Temperature Index** is usually identified with an "$_{\text{Outside}}$" subscript.

$$\mathbf{WBGT_{Outside} = 0.7[NWB] + 0.2[GT] + 0.1[DB]}$$

Where:

- $\mathbf{WBGT_{Outside}}$ is precisely as defined, under the designation of $\mathbf{WBGT_{Inside}}$, directly above on this page;
- **NWB** is also as defined directly above on this page;

GT is as defined on the previous page, namely, Page 5-5; &

DB = the **Dry-Bulb Temperature**, usually measured in °C; however, it should be noted for this relationship, too, that any temperature scale may be used for these parameters, so long as the units of every temperature parameter in the equation are consistent with the units of every other temperature parameter.

Temperature Related Time Weighted Averages

Equation #5-3:

Equation **#5-3** provides the relationship necessary for the determination of the **Effective Time Weighted Average WBGT Index**. This Index represents an average exposure over time, and at various different **WBGT Indices**. This formula is directly analogous to every other formula that is used to determine a Time Weighted Average.

$$\mathbf{WBGT_{TWA}} = \frac{\sum_{i=1}^{n}[\mathbf{WBGT_i}][\mathbf{t_i}]}{\sum_{i=1}^{n}\mathbf{t_i}} = \frac{[\mathbf{WBGT_1}][\mathbf{t_1}]+[\mathbf{WBGT_2}][\mathbf{t_2}]+\ldots+[\mathbf{WBGT_n}][\mathbf{t_n}]}{\mathbf{t_1}+\mathbf{t_2}+\ldots+\mathbf{t_n}}$$

Where: $\mathbf{WBGT_{TWA}}$ = the **Effective Time Weighted Average WBGT Index** that corresponds to a varied thermal exposure over time, usually measured in °C or °F;

$\mathbf{WBGT_i}$ = the **i**th **Wet Bulb Globe Temperature Index** that was measured over the Time Interval, $\mathbf{t_i}$, usually measured in °C or °F (either "$WBGT_{Indoor}$" or "$WBGT_{Outdoor}$", but NEVER a mixture of "$WBGT_{Indoor}$" and "$WBGT_{Outdoor}$"); &

$\mathbf{t_i}$ = the **i**th **Time Interval**, usually measured in hours; however, it can be measured in any useful and consistent units.

THERMAL STRESS PROBLEM SET

Problem #5.1:

What would be the Wet Bulb Globe Temperature Index, in °C, for a Quarry Worker in Connecticut, who must work on a sunny summer morning when the Outdoor Dry Bulb Temperature is 88°F; the Wet Bulb Temperature, 72°F; and the Globe Temperature, 102°F?

Applicable Definition:	Wet Bulb Globe Temperature Index	Page 5-4
Applicable Formulae:	Equation **#1-3**	Page 1-16
	Equation **#5-2**	Pages 5-5 & 5-6
Solution to this Problem:	Page 5-11	

Problem Workspace

Problem #5.2:

Later in the same afternoon, at the same quarry identified in Problem **#5.1**, rain clouds have gathered, and rain has commenced to fall. The Quarry Manager has covered the work area in the quarry pit with a large tarpaulin to protect his employees. If the Wet Bulb Temperature under the tarp has increased to 78°F, while the Globe Temperature has remained unchanged, what will be the new WBGT Index for this slightly different situation?

Applicable Definition:	Wet Bulb Globe Temperature Index	Page 5-4
Data from:	Problem **#5.1**	Page 5-7
Applicable Formulae:	Equation **#1-3**	Page 1-16
	Equation **#5-1**	Page 5-5
Solution to this Problem:	Pages 5-11 & 5-12	

Continuation of Workspace for Problem **#5.2**

Problem #5.3:

In a large midwest Steel Mill, the corporate Industrial Hygienist has evaluated the heat stress conditions to which each of the Mill's Open Hearth Operators is routinely exposed. These fully acclimatized workers are required, by their job description, to spend certain time periods in areas of the facility that are, quite understandably, very hot. For each time period spent in an area of substantial heat stress, these operators are required to spend a compensating time period in a cool rest area. This IH has determined site specific temperature conditions in this mill, as follows:

Location	Wet-Bulb Temperature	Globe Temperature
Open Hearth Area	117° F	175° F
Elsewhere in the Mill	102° F	93° F
Operator Rest Area	63° F	75° F

A typical Open Hearth Operator spends six 12-minute periods of each workday in the Open Hearth Area, and six corresponding 35-minute periods in the Rest Area. If these operators spend the balance of each 8-hour workday elsewhere in the Mill, what did the IH determine for the Time Weighted Average WBGT Index for a typical Open Hearth Operator?

Applicable Definition:	Wet Bulb Globe Temperature Index	Page 5-4
Applicable Formulae:	Equation **#1-3**	Page 1-16
	Equation **#5-1**	Page 5-5
	Equation **#5-3**	Page 5-6
Solution to this Problem:	Page 5-12	

Continuation of Workspace for Problem **#5.3**

Problem #5-4:

The Industrial Hygienist in Problem **#5.3** from the previous two pages recommended that the Time Weighted Average WBGT Index for a typical Open Hearth Operator be reduced. His recommendation was that the Steel Mill hire an additional Open Hearth Operator for each Shift. Doing so would decrease from six to five the number of time periods that each of these operators would have to spend in the Open Hearth Area. This IH also recommended that each compensating rest period be increased from 35 minutes to 45 minutes, recognizing that the balance of the time for each of these operators would still be spent elsewhere in the Mill. If these recommendations were implemented, what would the new improved Time Weighted Average WBGT Index be for a typical Open Hearth Operator?

Applicable Definition:	Wet Bulb Globe Temperature Index	Page 5-4
Data from:	Problem **#5.3**	Page 5-8
Applicable Formula:	Equation **#1-10**	Pages 1-19 & 1-20
	Equation **#5-3**	Page 5-6
Solution to this Problem:	Page 5-13	

Problem Workspace

SOLUTIONS TO THE THERMAL STRESS PROBLEM SET

Problem #5.1:

To solve this problem, we will have to employ Equation **#5-2,** from Pages 5-5 & 5-6, since we are dealing with evaluating a WBGT Index with a solar load (i.e., the subscript, "$_{\text{Outside}}$"); thus:

$$WBGT_{Outside} = 0.7[NWB] + 0.2[GT] + 0.1[DB] \qquad \text{[Eqn. \#5-2]}$$

$$WBGT_{Outside} = (0.7)(72) + (0.2)(102) + (0.1)(88)$$

$$WBGT_{Outside} = 50.40 + 20.40 + 8.8 = 79.6\,°F$$

The problem statement has asked for the Wet Bulb Globe Temperature Index in degrees Celsius; therefore, we must apply Equation **#1-3**, from Page 1-16, to convert the Fahrenheit temperature to its Celsius equivalent:

$$t_{Metric} = \frac{5}{9}\left[t_{English} - 32\right] \qquad \text{[Eqn. \#1-3]}$$

$$t_{Metric} = \frac{5}{9}[79.6 - 32] = \frac{(5)(47.6)}{9} = 26.4\,°C$$

$$\therefore \text{ The } WBGT_{Outside} \text{ Index } = 79.6°\,F = 26.4°C$$

Problem #5.2:

To solve this problem we will have to employ Equation **#5-1,** from Page 5-5, since this problem involves evaluating the WBGT Index without a solar load (i.e., the subscript = "$_{\text{Inside}}$" even though the situation is outside, but under a tarp which eliminates the solar load factor).

An additional subtlety to this problem is the seeming lack of a Wet Bulb Temperature. The clue to this answer, however, is in the problem statement. When it is raining, we know that the relative humidity is 100%; thus the wet bulb temperature equals the dry bulb temperature, since there would be no evaporative cooling of the thermometer bulb by the wet sheath that covers it:

$$WBGT_{Inside} = 0.7[NWB] + 0.3[GT] \qquad \text{[Eqn. \#5-1]}$$

$$WBGT_{Inside} = (0.7)(78) + (0.3)(102)$$

$$WBGT_{Inside} = 54.6 + 30.6 = 85.2°F$$

The problem statement has not specifically asked for the Wet Bulb Globe Temperature Index in degrees Celsius; however, to be fully consistent with Problem **#5.1**, we will again apply Equation **#1-3**, from Page 1-16, to convert the Fahrenheit temperature to its Celsius equivalent:

$$t_{Metric} = \frac{5}{9}\left[t_{English} - 32\right] \qquad \text{[Eqn. \#1-3]}$$

$$t_{Metric} = \frac{5}{9}[85.2 - 32] = \frac{(5)(53.2)}{9} = 29.6°C$$

∴ The $WBGT_{Inside}$ Index = 85.2°F ~ 29.6°C.

Problem #5.3:

To solve this problem, we will have to employ Equation **#5-1**, from Page 5-5, first, and then Equation **#15A**, from Page 3-35; thus:

$$WBGT_{Inside} = 0.7[NWB] + 0.3[GT] \qquad \text{[Eqn. \#5-1]}$$

1. For the Open Hearth Area:

$$WBGT_{Inside_{Open\ Hearth}} = (0.7)(117) + (0.3)(175)$$

$$WBGT_{Inside_{Open\ Hearth}} = 81.9 + 52.5 = 134.4°F$$

2. For the Operator Rest Area:

$$WBGT_{Inside\ _{Rest\ Area}} = (0.7)(63) + (0.3)(75)$$

$$WBGT_{Inside\ _{Rest\ Area}} = 44.1 + 22.5 = 66.6°F$$

3. For Elsewhere in the Mill:

$$WBGT_{Inside\ _{Elsewhere}} = (0.7)(102) + (0.3)(93)$$

$$WBGT_{Inside\ _{Elsewhere}} = 71.4 + 27.9 = 99.3°F$$

With these three $WBGT_{Inside}$ Indices known, we can now employ Equation **#5-3** from Page 5-6, to obtain the final TWA value requested:

$$WBGT_{TWA} = \frac{[WBGT_1][t_1] + [WBGT_2][t_2] + \ldots + [WBGT_n][t_n]}{t_1 + t_2 + \ldots + t_n} \qquad \text{[Eqn. \#5-3]}$$

$$WBGT_{TWA} = \frac{(134.4)(72) + (66.6)(210) + (99.3)(198)}{72 + 210 + 198}$$

$$WBGT_{TWA} = \frac{9,676.8 + 13,986.0 + 19,661.4}{480} = \frac{43,324.2}{480} = 90.26°F$$

Again the problem statement has not specifically asked for the Wet Bulb Globe Temperature Index in degrees Celsius; however, we will again apply Equation **#1-3**, from Page 1-16, to convert this Fahrenheit temperature to its Celsius equivalent, providing answers in both sets of units:

$$t_{Metric} = \frac{5}{9}\left[t_{English} - 32\right] \qquad \text{[Eqn. \#1-3]}$$

$$t_{Metric} = \frac{5}{9}[90.26 - 32] = \frac{(5)(53.2)}{9} = 32.37°C$$

∴ The $WBGT_{TWA}$ for a typical Open Hearth Operator = 90.26°F ~ 32.4°C.

Problem #5.4:

The solution to this problem will utilize some of the data developed in the solution of the previous problem — specifically, the three calculated $WBGT_{Inside}$ Indices. These values will be entered into Equation **#5-3**, from Page 5-6 to develop the desired solution:

$$WBGT_{TWA} = \frac{[WBGT_1][t_1] + [WBGT_2][t_2] + \ldots + [WBGT_n][t_n]}{t_1 + t_2 + \ldots + t_n} \quad \text{[Eqn. \#5-3]}$$

Remembering, from the solution to Problem **#5.3**, on the previous page, the following data:

1. For the Open Hearth Area: $WBGT_{Inside_{Open\ Hearth}} = 134.4°F$
2. For the Operator Rest Area: $WBGT_{Inside_{Rest\ Area}} = 66.6°F$
3. For Elsewhere in the Mill: $WBGT_{Inside_{Elsewhere}} = 99.3°F$

Next, we note the modified times that each of the Open Hearth Operators must spend in each of the areas of the facility:

1. In the Open Hearth Area: 60 minutes — reduced from 72 minutes [5 periods of 12 minutes each under the new regime vs. 6 periods of 12 minutes each under the former approach].
2. In the Operator Rest Area: 225 minutes — increased from 210 minutes [5 periods of 45 minutes each under the new regime vs. 6 periods of 35 minute each under the former approach].
3. Elsewhere in the Mill: 195 minutes — reduced from 198 minutes — arrived at in each case simply by subtracting the sum of the times spent in the Open Hearth Area + the Operator Rest Area from the time of a full work day, or 480 minutes, thus: [480 – 60 – 225 = 195 minutes] under the new regime, vs. [480 – 72 – 210 = 198 minutes] under the former approach.

Now applying Equation **#5-3**, we get:

$$WBGT_{TWA} = \frac{(134.4)(60) + (66.6)(225) + (99.3)(195)}{60 + 225 + 195}$$

$$WBGT_{TWA} = \frac{8{,}064.0 + 14{,}985.0 + 19{,}363.5}{480} = \frac{42{,}412.5}{480} = 88.36$$

∴ The improved $WBGT_{TWA}$ for a typical Open Hearth Operator resulting from the modified procedures recommended by the mill's Industrial Hygienist:

88.4°F ~ 31.3°C — an improvement of only ~ 1.9°F or ~ 1.1°C