**FUNDAMENTALS OF INDUSTRIAL HYGIENE, 6TH ED.**

**HOMEWORK #8**

**INDIVIDUAL MEASUREMENT OF THERMAL STRESS**

**Objective:** Students will become familiar with the fundamentals of thermal (heat) energy and its measurement, including the determination of potentially hazardous situations and the effectiveness of control measures.

**Background:**

Thermal stress is a significant physical agent in many workplace environments. Just considering routine out-of-doors work, air temperatures ranging from -20°F to 110°F can reasonably be expected in many places throughout the U.S. Heat stress contributed to the deaths of at least 655 American workers and the serious injury of 53,000 others from serious heat exposure from 1992 through 2012 alone. From 2011 to 2013, at least 35 workers died and 3,260 were seriously injured by exposure to dangerous heat levels (Source: U.S. Dept of Labor 2014). There are also numerous fatalities amongst the general public in non-occupational environments, including some rather high-profile athletes who have died.

It is disturbing that deaths from heat stress are still occurring, when most of the key controls are so basic, well-known, and straight-forward. Heat-stress related fatalities do not generally occur as a result of a sudden onset, rather they tend to build up over a period of time and the illnesses usually provide plenty of warning, yet fatalities continue to occur. Early recognition and awareness of the symptoms are clearly part of the solution, but safety and health professionals also need to be in a position to be able do something once warning signs are identified . . . and be willing to take appropriate actions.

Operations involving high air temperatures, radiant heat sources, high humidity, direct physical contact with hot objects, or strenuous physical activities have a high potential for inducing heat stress in employees engaged in such operations. Such places include: iron and steel foundries, nonferrous foundries, brick-firing and ceramic plants, glass products facilities, rubber products factories, electrical utilities (particularly boiler rooms), bakeries, confectioneries, commercial kitchens, laundries, food canneries, chemical plants, mining sites, smelters, and steam tunnels. Outdoor operations conducted in hot weather, such as construction, refining, asbestos removal, and hazardous waste site activities, especially those that require workers to wear semipermeable or impermeable protective clothing, are also likely to cause heat stress among exposed workers.

Age, weight, degree of physical fitness, degree of acclimatization, metabolism, use of alcohol or drugs, and a variety of medical conditions such as hypertension all affect a person's sensitivity to heat. However, even the type of clothing worn must be considered. Prior heat injury predisposes an individual to additional injury. It is difficult to predict just who will be affected and when, because individual susceptibility varies. In addition, environmental factors include more than the ambient air temperature. Radiant heat, air movement, conduction, and relative humidity all affect an individual's response to heat. The American Conference of Governmental Industrial Hygienists (ACGIH - 1992) states that workers should not be permitted to work when their deep body temperature exceeds 38°C (100.4°F).

Conceptually, work can occur in one of five zones along the continuum of thermal stress. In the middle is the *comfort zone*, where the demands for physiological adaptation are modest and productivity should be the greatest. On either side of the comfort zone are the *discomfort zones* for heat and cold stress. Under these conditions, most people should be able to safety work without experiencing a disorder related to the stress. They may report sensations of cold or heat, productivity and quality of work may decrease, and the risk of accidents may increase. The *health risk zones* for heat and cold stress are the outer zones of the thermal stress continuum. The physiological adaptations have reached their limits and work capacity is severely limited. In the health risk zones, the likelihood of heat and cold stress-related disorders increases markedly. The goal of most evaluation schemes for occupational heat and cold stress is to limit exposures at the transition to the health risk zone. Of course, there are no firm boundaries to these zones because the boundaries depend on the environment (e.g., wind, altitude), individuals (e.g., body fat content, physical health), and season as well as many unknown variables (e.g., acclimation). For example, in the fall, when the temperature drops to around 50°F, students start to bundle up. In the spring, when the temperature climbs to around 50°F, students start running around in shorts and T-shirts.

The management of thermal exposures has long been an issue not only because of the extremes of the environment, but also as a result of the variability associated with the human body. Heat stress has proven to be a key issue in industry as well as day to day life, not only impacting directly on the individual but also indirectly as a contributing factor in many safety incidents. Assessment of the hot thermal environment can best be approached via a systematic three step approach that may be applied to a number of varying scenarios where there is a potential risk to heat stress.

The three tiered approach for the assessment of exposure to heat has been designed such that it may be applied to a number of varying scenarios where there is a potential risk to heat stress. The suggested approach involves a three-stage process dependent on the severity and complexity of the situation. It allows for the application of the right tool for a scenario utilizing a variation of risk assessment approaches from simple to complex.

The first level or the basic thermal risk assessment was primarily designed as a *qualitative assessment* which does not require specific technical skills in its application or interpretation. In fact it was originally developed for use by front-line employees to assist them in better understanding the mechanisms and the many different impacts associated with thermal assessments. This was done by asking the employee to rate specific aspects of the task and environment that impact on their thermal stress on a simple check sheet. Its intent was to show that there are many aspects of the work environment that need to be considered, not just a single thermometer reading. In fact, in the original version of the basic thermal assessment there was no actual measurement required. The use of the wet bulb globe temperature (WBGT) temperature in the initial assessment was only added later to help balance off the subjective and qualitative nature of the evaluation with some actual measures.

The second level of the process begins to look more towards a *quantitative risk approach* and requires the measurement of a number of environmental and personal parameters such as dry bulb and dry globe temperatures, relative humidity, air velocity, metabolic work load, and clothing insulation. These measures are then utilized in a heat stress index to determine the projected level of impact on the group or individual. The indices used in this step can be empirical, direct, or rational indices. They may result in a temperature, predicted core temperature, or metabolic work limit. These calculations are then used to determine an outcome and apply allowable exposure times for groups of people exposed. The indices are usually applied with certain qualifications (e.g., health, hydration, fitness, and in some cases, age.

The third step approaches from a more *quantitative risk perspective* in that it utilizes measurements based on an individual’s strain and reactions to the thermal stress to which they are being exposed. This direct measurement takes into account the variables (age, fitness, etc.) for which assumptions were made in the second step of the assessment (i.e., indices). This approach measures the actual strain on the individual rather than basing it around a group. The assessment provides a more accurate result and a greater level of confidence in relation to the impact on the individual regardless of the conditions and importantly, includes the impact of personal protective equipment PPE.

It should be noted that the differing levels of risk assessment do require increasing levels of technical expertise, and while a Level 1 assessment could be undertaken by a variety of individuals with limited technical skills, the use of a Level 3 assessment should be restricted to someone with specialist knowledge and skills.

While the majority of discussions related to thermal stress focus on heat-stress and, to a much lesser amount, cold-stress, other factors should be considered. For example, elevating ambient temperatures above thermo-neutrality can exacerbate the toxicity of most air pollutants, insecticides, and other toxic chemicals. However, the evaluation of the safety and toxicity of toxicants and drugs is usually performed by testing on mice and rats at sub-thermally neutral temperatures for these test subjects (~22°C, 72°F). When exposed to chemical toxicants under these relatively cool conditions, rodents typically undergo a controlled hypothermic response (reduction in core temperature). While reducing core temperature delays the clearance of most toxicants from the body, a mild hypothermia also improves recovery and survival from the toxicant. Raising ambient temperature to thermo-neutrality and above increases the rate of clearance of the toxicant, it also increases its toxic effect. Heat-stress, combined with work or exercise, is likely to worsen toxicity, particularly in large mammals (including humans), which do not decrease their core body temperatures as much in response to a toxicant. Heat stress can worsen toxic outcome in humans through a variety of mechanisms. For example, heat-induced sweating and elevation in skin blood flow accelerates uptake of some insecticides.

**Part I: Model of Thermal Balance**

Three factors influence the degree of thermal stress:

- climatic factors (most obvious . . . temperature, humidity, radiant heat, wind speed);

- work demands (production of internal heat energy); and

- clothing (insulation . . . from heat gain or heat loss).

The tradition has been to describe thermal balance by an equation with major avenues of heat exchange between the body and the environment represented by terms in an equation.

*S = (M – W) + R + C + K + (Cresp – Eresp) – E*

where: *S* = heat storage rate (gain [+] or loss [-]) (in *watts/min* or *kcal/min*)

 *M* = metabolic rate (internal heat generation) (in *watts/min* or *kcal/min*)

 *W* = external work rate (energy delivered to environment) (in *watts/min* or *kcal/min*)

 *R* = radiant heat exchange rate (gain [+] or loss [-])(in *watts/min* or *kcal/min*)

 *C* = convective heat exchange rate (gain [+] or loss [-])(in *watts/min* or *kcal/min*)

 *K* = conductive heat exchange rate (gain [+] or loss [-])(in *watts/min* or *kcal/min*)

 *Cresp* = rate of convective exchange by respiration (gain [+] or loss [-])(in *watts/min* or *kcal/min*)

 *Eresp* = rate of evaporative heat loss by respiration(in *watts/min* or *kcal/min*)

 *E* = rate of evaporative heat loss(in *watts/min* or *kcal/min*)

Note: Heat exchange represented by *R*, *C*, *K*, and *Cresp* can be in either direction.

- A positive value for any of these terms means that heat is gained by the body.

- A negative value means that heat is lost from the body.

Note: The values for *M* and *(M – W)* are only positive and represent a heat gain.

Note: The values for *W*, *Eresp*, and *E* are negative and always represent a heat loss.

** *S* – heat storage rate**

If the value for *S* is zero, the body is in thermal equilibrium, and the heat gain is balanced by heat loss from the body.

- If *S* is positive, the body is gaining heat at the rate indicated by the value of *S*.

- If *S* is negative, the body is losing heat at the rate indicated by the value of *S*.

** *M* – metabolic rate**

Chemical reactions occur continuously inside the body. These serve to sustain life (*basal metabolism*) and meet the demands of work (*muscle metabolism*). Because the conversion from chemical energy to kinetic energy is inefficient, increased metabolism results in increased rates of heat gain to the person.

** *W* – external work rate**

*W* is the amount of energy that is successfully converted from internal chemical energy to mechanical work on external objects. This route of energy transfer is called external work and it does not contribute to body heat.

** *R* – radiant heat exchange rate (radiation)**

Solid bodies of different temperatures have a net heat flow from the hotter surface to the cooler surface by electromagnetic radiation (primarily infrared radiation). The rate of heat transfer by radiation depends on the average temperature of the surrounding solid surfaces, skin temperature, and clothing.

** *C* – convective heat exchange rate (convection)**

The exchange of heat between the skin and the surrounding air is referred to as convection. The direction of heat flow depends on the temperature difference between the skin and air.

- If air temperature > skin temperature, *C* is positive and heat flows from the air to the skin.

- If the air is < skin temperature, *C* is negative and heat flows from the body.

** *K* – conductive heat exchange rate**

When two solid bodies are in contact, heat will flow from the warmer body to the cooler body. The rate of heat transfer depends on the difference in temperatures between the skin and the solid surface. In addition, the thermal conductivity of the solid body that the person contacts and clothing (insulation) that may separate the person from the solid surface play a role.

** *Cresp*– rate of convective heat exchange by respiration**

Air is moved in and out of the lungs, which have a large surface area. This means that there is an opportunity to gain or lose heat. The rate of heat exchange depends on the air temperature and the volume of air moved in and out of the lungs.

** *Eresp* – rate of evaporative heat loss by respiration**

The large surface area of the lungs provides ample opportunity to lose heat by evaporation. The rate of heat exchange depends on the humidity of the inhaled air and the volume of air moved in and out of the lungs.

** *E* – rate of evaporative heat loss**

Sweat on the skin surface will absorb heat from the skin when evaporating into the air. The rate of evaporative heat loss depends on the amount of sweating, air movement, ambient humidity, and clothing.

Note: Because *W*, *K*, *Cresp*, and *Eresp* are small relative to the other routes of heat exchange in industrial applications, they are usually ignored. Thus, the original formula may be re-written as a general statement of heat balance:

*S = M + R + C – E*

**Part II: Heat Stress**

In response to heat stress, workers will exhibit *physiological responses*, adjusting breathing, sweating, and changing their blood flow as the body attempts to maintain thermo-neutrality. These physiological adaptations are collectively known as *heat strain*. The most readily accessible indicators for measurement are temperature, heart rate, and water loss. Based on these readings, the health and safety professional can begin to see if a more detailed evaluation is necessary. When selecting workers to sample, it is important not to be biased toward those that appear to be the most tolerant. The sampling process should be random or favoring those who appear to be having more problems.

** core body temperature**

The heat generated by muscular work heats the deep body tissues, and there is a tendency for core temperature to increase. Blood circulating through the core picks up heat energy, and is then directed to the skin where the blood is cooled. The cooler blood returns to the core to pick up more heat energy. The skin is the site of heat exchange with the environment. Convection and radiation depend on temperature differences between the skin and the environment. In addition, the skin secretes sweat on to the surface. As the water evaporates, it removes more heat energy from the skin, cooling the skin surface. Core temperature is estimated by adding 0.5°C or 1°F to the oral temperature reading.

- If core temperature is above 100.4°F, the heat stress is high enough to warrant evaluation.

** heart rate**

Heart rate is an important factor in assessing heat strain because it reflects the demands on the cardiovascular system to move blood (and het) from the core to the skin. The total blood flow through the heart is proportional to the metabolic rate and inversely proportional to the temperature difference between the core and the skin. Sometimes, skin temperatures increases because

evaporative cooling is limited or the net heat gain from *R + C* is high. As the skin temperature increases toward core temperature, more blood must be delivered to the skin to achieve the same rate of cooling. Individuals with high blood pressure or some heart conditions and people who take diuretics (water pills) may be more sensitive to heat exposure.

- If the average heart rate over a day is greater than 110 beats per minute (*bpm*), the work and heat stress may be excessive.

- If peak heart rates are above a nominal threshold of 160 *bpm*, the demands of the work should be evaluated.

** sweat rate**

Sweat rate (and total sweat volume) is another physiological parameter in the measure of physiological strain. The greater the level of heat stress, the greater is the sweat loss. Under ideal conditions, the body balances heat gains with losses so that the storage rate (*S*) is zero. This is accomplished by increasing the sweating rate until evaporative cooling is sufficient to remove the heat generated by metabolism plus any heat gained from (or lost to) the environment through *R* + *C*. The required evaporative cooling is denoted as *Ereq*, which marks the degree of physiological adjustment required to establish a thermal equilibrium between the body and the environment so that the body does not store heat.

The earlier equation: *S = M + R + C – E* becomes *Ereq = M + R + C*

- If there is more than 1.5 percent loss of body weight (1.5 *lbs* for every 100 *lbs* body weight), excessive dehydration is likely and an evaluation is appropriate.

Note: The body has a natural ability to increase the tolerance to heat stress exposures through a process called *acclimation (acclimatization)*. As people become acclimated, they are able to sweat more and, therefore, increase their cooling capability. Further, people behave in adaptive working (pacing) to avoid extreme heat buildup in the core temperatures.

Heat stress not only induces physiological changes, but also results in *behavioral changes*. Likely behaviors associated with heat stress are:

** actions that reduce exposures**

- adjusting clothing to increase evaporative losses

- slowing the work rate

- taking small breaks

- taking short-cuts in work methods

** changes in attitudes**

- irritability

- low morale

- absenteeism

** unsafe acts**

- increased number of errors

- increased number of machine breakdowns

- taking short-cuts in work methods

**Part III: ACGIH TLV for Heat Stress and Strain**

The current ACGIH TLV for heat stress and strain recognizes the difference between eight-hour and short-duration exposures, and the value of physiological monitoring in the evaluation and control of heat stress. Evaluation of heat-stress potential requires the examinations of three separate components to the hazard: 1) work-load assessment (metabolic rate required to perform a task - internal heat generation); 2) assessment of environmental conditions (external heat sources); and 3) assessment of clothing (effect on energy loss from body).

**Work-Load Assessment**

Under conditions of high temperature and heavy workload, the safety and health professional should determine the work-load category of each job.

Metabolic rate is the rate of internal heat generation, which must be dissipated from the body to maintain thermal equilibrium.

First, there is a base level of metabolism (i.e., *basal metabolism*) that is necessary to support life.

Beyond basal metabolism, there is a work-driven metabolism that is largely the result of muscular effort.

The greatest metabolic rate resulting from muscular effort occurs when the muscles exert a force with motion (*dynamic work*), and much less metabolic demand is required to exert a force with no motion (isometric contraction or *static work*).

** method #1**

A very simple method to assess metabolic rate is to assign the work demands into one of three-to-five categories of metabolic rate (e.g., light, moderate, heavy, very heavy).

- light work: up to 200 *kcal/hour*

- moderate work: 200-350 *kcal/hour*

- heavy work: 350-500 *kcal/hour*

- very heavy work: 500-650 *kcal/hour*

** method #2**

Another simple method is to look for similar activities in published tables of metabolic rates for specific activities, and then determine the work-load category by averaging metabolic rates for the tasks.

** method #3**

A third approach is to calculate the metabolic rate for each particular job.

Some discipline is required in the assessment of metabolic rate.

- the first step is to divide the job into discrete, homogenous tasks, and then determine their duration (a videotape is often helpful in this step).

- a metabolic rate can then be assigned to each task.

The metabolic rate can be estimated by summing together five components:

*Mtask = B + P + A + H + V*

where: *B* = basal metabolism

 *P* = posture

 *A* = activity based on body movement

 *H* = horizontal travel (rate of horizontal travel)

 *V* = vertical travel (rate of vertical travel)

- finally, the time-weighted average for metabolic rate can be determined (TWA-*M*).

where: *M* = metabolic rate

 *t* = time (in minutes)

Note: Where heat conditions in the rest area (i.e., *cool rest area*) are different from those in the work area, the metabolic rate (*M*) should be calculated using a time-weighted average including the time spent in the cool rest area.

**Examples of metabolic rates for different activities include:**

** light hand work (writing, hand knitting)**

** heavy hand work (typewriting)**

** light work with one arm (brush painting)**

** heavy work with one arm (hammering nails: shoemaker, upholsterer)**

** light work with two arms (metal filing, wood planning, raking)**

** heavy work with two arms (positioning loaded boxes, squeezing/compressing materials)**

** moderate work with whole body (cleaning a floor, beating carpets, stacking firewood)**

** heavy work with whole body (railroad track laying, digging with a shovel, brush clearing)**

Table 1 provides the results of calculations using the metabolic rate formula for a variety of different activities.

**Table 1:** Estimated Values of Metabolic Rates for Tasks

**Body Position and Movement (kcal/min\*)**

**Basal Metabolism (*B*)** 1.0

**Posture Metabolism (*P*)**

Sitting 0.3

Standing 0.6

Walking (level)\*\* 2.0-3.0

Walking (uphill)\*\* add 0.8 for every meter (yard) of rise

**Activity Metabolism (*A*) Average Range**

Hand (light) 0.4 0.2-1.2

Hand (heavy) 0.9

One Arm (light) 1.0 0.7-2.5

One Arm (heavy) 1.7

Both Arms (light) 1.5 1.0-3.5

Both Arms (heavy) 2.5

Whole Body (light) 3.5 2.5-15.0

Whole Body (moderate) 5.0

Whole Body (heavy) 7.0

Whole Body (very heavy) 9.0

\*Values given for a “standard” worker of 70 kg (154 lbs.) body weight and

 1.8m2 (19.4 ft2) surface area.

Source: ACGIH 1992

\*\*These values include the horizontal travel (H) portion of the equation.

The equation then becomes *M = B + P + A + V*.

**Example Problem: An automobile assembly line worker must walk along the assembly line keeping pace with the vehicle they are working on while simultaneously lifting and positioning doors into position and then tightening the bolts that hold the door to the vehicle frame using a heavy hand-tool. A videotape of the worker was analyzed in 1-hour blocks and showed the worker performing these duties for an entire 8-hour shift, with a 15-minute break in the morning and afternoon and a 30-minute break for lunch. During breaks and lunch, the worker is predominately sitting. Determine the work category (light, moderate, heavy, very heavy) for this worker.**

**Step #1: Calculating the metabolic rate required to perform the task:**

*Mtask = B + P + A + V*

where: *B* = basal metabolism

 *P* = posture (includes rate of horizontal travel)

 *A* = activity based on body movement

 *V* = vertical travel (rate of vertical travel)

**Using values from Table 1:**

**Basal Metabolism (*B*) = 1.00 *kcal/min***

**Posture Metabolism (*P*) (walking level) = 2.00 *kcal/min***

**Activity Metabolism (A)**

**Light Work (whole body) (50%) 0.5  3.5 *kcal/min* = 1.75 *kcal/min***

**Heavy Work (two arms) (50%) 0.5  2.5 *kcal/min* = 1.25 *kcal/min***

*Mtask = 1.00 kcal/min + 2.00 kcal/min + 3.00 kcal/min = 6.00 kcal/min (360 kcal/hour)*

**Step #2: Calculating the average metabolic rate for the worker:**

where: *M* = metabolic rate

 *t* = time (in minutes)

**Worker’s Schedule**

 ***(t)* *(M)* *(M)  (t)***

8:00-9:00 AM (60 *min*) work (6 *kcal/min*) (*M1*)(*t*1) = (6 *kcal/min*)  (60 *min*) = 360 *kcal min/min*

9:00-10:00 AM (60 *min*) work (6 *kcal/min*) (*M2*)(*t*2) = (6 *kcal/min*)  (60 *min*) = 360 *kcal min/min*

10:00-10:15 AM (15 *min*) break (1.3 *kcal/min*)\* (*M3*)(*t*3) = (1.3 *kcal/min*)  (15 *min*) = 19.5 *kcal min/min*

10:15-11:00 AM (45 *min*) work (6 *kcal/min*) (*M4*)(*t*4) = (6 *kcal/min*)  (45 *min*) = 270 *kcal min/min*

11:00-12:00 AM (60 *min*) work (6 *kcal/min*) (*M5*)(*t*5) = (6 *kcal/min*)  (60 *min*) = 360 *kcal min/min*

12:00-12:30 PM (30 *min*) break (1.3 *kcal/min*) (*M6*)(*t*6) = (1.3 *kcal/min*)  (30 *min*) = 39 *kcal min/min*

12:30-1:00 PM (30 *min*) work (6 *kcal/min*) (*M7*)(*t*7) = (6 *kcal/min*)  (30 *min*) = 180 *kcal min/min*

1:00-2:00 PM (60 *min*) work (6 *kcal/min*) (*M8*)(*t*8) = (6 *kcal/min*)  (60 *min*) = 360 *kcal min/min*

2:00-2:30 PM (30 *min*) work (6 *kcal/min*) (*M9*)(*t*9) = (6 *kcal/min*)  (30 *min*) = 180 *kcal min/min*

2:30-2:45 PM (15 *min*) break (1.3 *kcal/min*) (*M10*)(*t*10) = (1.3 *kcal/min*)  (15 *min*) = 19.5 *kcal min/min*

2:45-3:00 PM (15 *min*) work (6 *kcal/min*) (*M11*)(*t*11) = (6 *kcal/min*)  (15 *min*) = 90 *kcal min/min*

3:00-4:00 PM (60 *min*) work (6 *kcal/min*) (*M12*)(*t*12) = (6 *kcal/min*)  (60 *min*) = 360 *kcal min/min*

 *total = 480 min total =* 2598 *kcal min/min*

*\*Metabolic rate for breaks determined at 1.0 kcal/min for basal metabolism + 0.3 kcal/min for sitting.*

 (324 kcal/hour . . . moderate work)

**Assessment of Environmental Conditions**

The environmental factors that are central to the assessment of heat stress are:

- air temperature,

- humidity,

- air speed, and

- average temperature of the solid surroundings

** dry-bulb temperature (*Tdb*)**

The dry-bulb temperature is the direct measure of air temperature. The temperature sensor is surrounded by air, which is allowed to move freely around the sensor. The sensor; however, may be influenced by radiant heat sources and, therefore, should be shielded from them.

** psychrometric wet-bulb temperature (*Tpwb*)**

The psychrometric wet-bulb temperature is based on the degree of evaporative cooling that can occur. In practice, a wetted wick is placed around a temperature sensor and enough air is forced over the wick to maximize the rate of evaporative cooling (> 3 *m/s*). Classically, the device used to measure the psychrometric wet-bulb temperature is the *sling psychrometer*.

The amount of temperature reduction that can be achieved depends directly on the amount of water vapor in the air (i.e., relative humidity). When humidity is high, the reduction in temperature is low, and *vice versa*.



** ambient water vapor pressure (*Pv*)**

The ambient water vapor pressure is commonly known as *humidity*. There are two ways that humidity is expressed: relative and absolute.

- *specific humidity*

At any given temperature, the amount of water vapor that air can hold has a maximum value . . . the *saturation point*. Hotter air can hold more water vapor than colder air and, therefore, the saturation point of hot air will be higher than that for colder air. Just because the air is at a certain temperature, it doesn’t mean that it will be holding the maximum amount of water vapor that it can. Specific humidity relates how much water vapor is actually in the air (*g* of water vapor/*kg* of air).

- *relative humidity*

Relative humidity is the ratio of how much water vapor the air could possibly hold at that temperature *versus* how much water vapor is actually in the air. Thus, if air at 30°*C* (86°*F*) can hold a maximum of 28 *g*H20/*kg*air but actually only contains 14 *g*H20/*kg*air, the relative humidity would be 50% (14 ÷ 28 = 0.5 or 50%).

Note: By comparing the dry-bulb temperature (*Tdb*) and the psychrometric wet-bulb temperature (*Tpwb*), the amount of cooling achieved through evaporation is obtained.

This can then be compared to a chart to determine the relative humidity, even when the specific humidity is not known (see chart on following page).



**Example Problem:** From the chart above, it is seen that air at 35*°C* (95*°F*) can hold a maximum of 38 *g*H2O/*kg*air. The air is actually holding 23 *g*H2O/*kg*air. What is the specific humidity and relative humidity?

Specific humidity is the amount of water vapor that is actually in the air . . . 23 *g*H2O/*kg*air

Relative humidity is how much water vapor is in the air compared to the maximum amount it could hold at that temperature (as a percent) . . . 23 *g*H2O/*kg*air ÷ 38 *g*H2O/*kg*air = 0.605 = 60.5%

**Example Problem:** Following the correct use of a sling psychrometer, the dry-bulb temperature was found to be 18*°C* (64.4*°F*) and the wet bulb temperature was found to be 12*°C* (53.6*°F*). Use the chart below to determine the relative humidity?

Determine the temperature depression . . . 18*°C* – 12*°C* = 6*°C*

Find the dry-bulb temperature on the left-hand column (18*°C*).

Follow the dry-bulb temperature row across until you get to the temperature depression column.

The value in the cell where the row and column meet is the relative humidity . . . 48%



** natural wet-bulb temperature (*Tnwb*)**

Natural wet-bulb temperature is similar to the psychrometric wet-bulb except that air is allowed to flow over the sensor naturally, rather than being forced.

** air speed (*Vair*)**

Air speed is measured using an appropriate anemometer. Because the speed will vary in time and space, an average value is used.

** globe temperature (*Tg*)**

Globe temperature responds to radiant heat from the solid surroundings and convective heat from the ambient air. The globe temperature is classically measured using a six-inch, thin-walled, copper sphere that has been painted matte black on the outside. The temperature sensor is placed at the center of the globe. Globe temperature is used to estimate the average wall temperature of the surroundings.

** effective temperature (*ET*) and corrected effective temperature (*CET*)**

These were indices of the thermal environment first developed to equate thermal sensation, and later used to describe thermal stress. *ET* was determined from a nomogram that requires knowledge of *Tdb*, *Tpwb*, and *Vair*.

Note: Because *ET* did not account for radiant heat, *CET* was proposed (it uses *Tg* instead of *Tdb*).

Note: Neither *ET* nor *CET* is used to evaluate heat stress today. Instead, a new index was required that was indicative of thermal stress from the environment. The wet-bulb globe temperature (*WGBT*) was the evolutionary step from *ET* and *CET*.

** wet-bulb globe temperature (*WBGT*)**

Wet-bulb globe temperature is an index of environmental heat.

- in environments that are indoors, in the shade, or on a cloudy day, it is computed as:

*WBGTin = 0.7Tnwb + 0.3Tg*

- under conditions of direct sunlight (outdoors, no cloud cover), it is computed as:

*WBGTout = 0.7Tnwb + 0.2Tg + 0.1Tdb*

where: *WGBT* = wet bulb globe temperature index

 *T*nwb = natural wet-bulb temperature

 *T*db = dry-bulb temperature

 *T*g = globe temperature

Note: The WBGT for continuous all-day or several-hour exposures should be averaged over a 60-minute period. Intermittent (short-term) exposures should be averaged over a 120-minute period. These averages should be calculated using the following formula:

A two-hour time-weighted average effective temperature (*WGBT*2hr) is used to measure a short-term exposure to heat stress. The short-term exposure is important for identifying exposures of only a few hours, since even short exposures can be hazardous. On the other hand, an exposure of only a few minutes is not likely to be hazardous unless the temperature is extreme.

Representative measurements must be made during the time period chosen. This period should include the hottest working conditions during the day. If the worker is exposed to differing levels of heat stress during the two hours, the *WBGT*2hr in each area and the time spent in each area must be determined. This would include time spent on breaks in cooler areas.

**Example Problem:** Temperature measurements were taken in a food processing plant. One employee was monitored. The employee operated one machine in the production area, and took breaks in a separate room.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Sample** | **Sampling****Period** | **Time****(min)** | **Area****Sampled** | **Activity** | **Readings from Heat Stress Monitor** |
| ***Tg*** | ***Tdb*** | ***Tnw*b** | ***WGBT*** |
| 1 | 8:00 to 8:30 | 30 | Cooker | Product rotation – moderate work | 98 | 95 | 80 | *85* |
| 2 | 8:30 to 8:50 | 20 | Cooker | Unloading – moderate work | 97 | 90 | 78 | *84* |
| 3 | 8:50 to 9:15 | 25 | Cooker | Finishing – moderate work | 95 | 90 | 78 | *83* |
| 4 | 9:15 to 9:30 | 15 | Break Room | Break | 80 | 78 | 73 | *75* |
| 5 | 9:30 to 10:00 | 30 | Cooker | Unloading – moderate work | 98 | 94 | 80 | *85* |

Step #1: Determine the *WBGT* for each sampling period.

*WBGTin = 0.7Tnwb + 0.3Tg*

period 1: (0.7 *°F*) + (0.3  98*°F*) = 56.0*°F* + 29.4*°F* = 85.4*°F*

period 2: (0.7 78*°F*) + (0.3  97*°F*) = 54.6*°F* + 29.1*°F* = 83.7*°F*

period 3: (0.7 78*°F*) + (0.3  95*°F*) = 54.6*°F* + 28.5*°F* = 83.1*°F*

period 4: (0.7 73*°F*) + (0.3  80*°F*) = 51.1*°F* + 24.0*°F* = 75.1*°F*

period 5: (0.7  80*°F*) + (0.3  98*°F*) = 56.0*°F* + 29.4*°F* = 85.4*°F*

Step #2: Since the worker took breaks in a cool rest area, it is appropriate to determine heat stress based on a two-hour time-weighted average.

Step #3: The two-hour time-weighted average *WBGT*, along with the workload (light, moderate, or heavy) is used to determine if an overexposure has occurred. From Table 2, below, it is noted that the permissible exposure limit for moderate workload under a continuous regime is 80°F. In this example, an overexposure has occurred.

**Table 2: Permissible Heat-Exposure Threshold Limit Value**

 **----- Work Load (in °C and °F WBGT)-----**

**Work/Rest Regimen Light Moderate Heavy**

**Continuous Work 30.0°C (86°F) 26.7°C (80°F) 25.0°C (77°F)**

**75% Work/25% Rest (each hour) 30.6°C (87°F) 28.0°C (82°F) 25.9°C (78°F)**

**50% Work/50% Rest (each hour) 31.4°C (89°F) 29.4°C (85°F) 27.9°C (82°F)**

**25% Work/75% Rest (each hour) 32.2°C (90°F) 31.1°C (88°F) 30.0°C (86°F)**

These TLV's are based on the assumption that nearly all acclimatized, fully clothed workers with adequate water and salt intake should be able to function effectively under the given working conditions without exceeding a deep body temperature of 38°C (100.4° F).

**Clothing Adjustment Factor (CAF)**

Ideally, free movement of cool, dry air over the skin’s surface maximizes heat removal by both evaporation and convection.

Evaporation of sweat from the skin is the predominant heat removal mechanism. Water vapor impermeable, air impermeable, and thermally insulating clothing, as well as encapsulating suits and multiple layers of clothing, severely restrict heat removal.

With heat removal hampered by clothing, metabolic heat may produce excessive strain, even when ambient conditions are considered cool.

The original concept for the heat stress limits adopted by ACGIH was that the threshold for heat stress can be marked by environmental conditions (*WBGT*) that are adjusted for metabolic rate.

The underlying data were based on ordinary work clothes; however, ACGIH promoted clothing adjustment factors for a variety of additional ensembles through a revision in the TLVs for heat stress in 1990.

As approved, there were adjustment factors for three other clothing ensembles.

To extend and further understand adjustment factors, adjustments for commercially available clothing ensembles and prototype ensembles have been examined.

The fundamental principle of the assignment of an adjustment factor to an ensemble begins with establishing critical environmental conditions in which test subjects were just able to maintain thermal equilibrium.

**Table 3:** *WBGT* Clothing Adjustment Factors (CAFs) for Different Clothing Ensembles (in *°C*-WBGT)

**Ensemble CAF**

Work Clothes 0*°C* (0*°F*)

Cloth Overalls 0*°C* (0*°F*)

SMS Non-woven Coveralls 0.5*°C* (1.0*°F*)

*(single layer)*

Tyvek® Coveralls 1*°C* (1.8*°F*)

*(single layer)*

Vapor-Barrier Apron 4*°C* (7.2*°F*)

*(long sleeves and length, over cloth coveralls)*

Double Layer of Woven Clothing 3*°C* (5.4*°F*)

NexGen® Coveralls 2.5*°C* (4.5*°F*)

*(single layer)*

Micro-porous Coveralls 6*°C* (10.8*°F*)

Vapor-Barrier Coveralls 10*°C* (18.0*°F*)

*(single layer)*

Vapor-Barrier Coveralls 11*°C* (19.8*°F*)

*(single layer, with hood)*

Vapor-Barrier Coveralls 12*°C* (21.6*°F*)

*(over cloth coveralls, w/o hood, w/ respirator)*

Hood\* +1*°C* (1.8*°F*) \*(add to CAF of the ensemble *w/o* hood)

Full-Face Negative +0.3 *°C* (0.5*°F*) \*(add to CAF of the ensemble *w/o*

Pressure Respirator\* respirator)

\*The CAF-values given should be added to the WBGT temperature for correction for clothing.

**Heat Stress Screening**

The *WBGT* offers a useful, first-order index of the environmental contribution to heat stress.

It is influenced by air temperature, radiant heat, air movement, and humidity.

As an approximation, it does not fully account for all the interaction between a person and the environment, and cannot account for special conditions such as heating from a radiofrequency/microwave source.

Because *WBGT* is only an index of the environment, the screening criteria are adjusted for the contributions of work demands (metabolic rate) and clothing (rate of heat loss by evaporation/convection).

Table 4 provides *WBGT* criteria suitable for screening purposes, and it can be used when the clothing adjustment factor for ensembles identified in Table 3 are added to the *WBGT*.

As metabolic rate increases (i.e., work demands increase), the criteria values in the table decrease to ensure that most workers will not have a core body temperature above 38*°C* (100.4*°F*).

Based on metabolic rate category for the work and the approximate proportion of work conducted within an hour, a *WBGT* criterion can be found in Table 4 for the TLV and for the action limit.

If the measured time-weighted average *WBGT* adjusted for clothing is less than the table value for the action limit, there is little risk of excessive exposures to heat stress.

If the conditions are above the action limit, but below the TLV, then general controls should be considered.

If there are reports of the symptoms of heat-related disorders (e.g., fatigue, nausea, dizziness, lightheadedness), then the analysis should be reconsidered.

**Table 4:** Screening Criteria for Heat Stress

**%Work Light Moderate Heavy Very Heavy**

 *Action Limit Screening [°C-WBGT]*

75 to 100 28.1*°C* ( 82.6*°F*) 25.0*°C* (77.0*°F*) ----- -----

50 to 75 28.7*°C* (83.7*°F*) 26.0 *°C* (78.8*°F*) 24.2*°C* (75.6*°F*) -----

25 to 50 29.3*°C* (84.7*°F*) 27.2*°C* (81.0*°F*) 25.7*°C* (78.3*°F*) 24.6*°C* (76.3*°F*)

0 to 25 30.0*°C* (86.0*°F*) 28.8*°C* (83.8*°F*) 27.8*°C* (82.0*°F*) 27.0*°C* (80.6*°F*)

 *TLV Screening [°C-WGBT]*

75 to 100 30.8 *°C* (87.4*°F*) 28.2*°C* (82.8*°F*) ----- -----

50 to 75 31.2 *°C* (88.2*°F*) 29.0*°C* (84.2*°F*) 27.6*°C* (81.7*°F*) -----

25-50 31.8*°C* (89.2*°F*) 30.1*°C* (86.2*°F*) 28.8*°C* (83.8*°F*) 27.9*°C* (82.2*°F*)

0 to 25 32.3*°C* (90.1*°F*) 31.3*°C* (88.3*°F*) 30.5*°C* (86.9*°F*) 29.8*°C* (85.6*°F*)



**SHM 471 – HOMEWORK #8**

**FUNDAMENTALS OF INDUSTRIAL HYGIENE, 6TH ED.**

**INDIVIDUAL MEASUREMENT OF THERMAL STRESS**

**Name:**

**EXERCISES:** Perform the calculations identified below. Show your work neatly and clearly in a manner similar to the examples provided above (i.e., write the formula and define each variable in the formula where requested, show steps of your calculations). *(1 point each – 18 pts. total)*

**Part I: Calculation of Relative Humidity**

1a) The air temperature on a construction site is measured and a dry-bulb reading of 13*°C* (55.4*°F*) is obtained. The amount of water vapor in the air is 7 *g*H2O/*kg*air.

What is the specific humidity?

What is the maximum amount of water vapor the air can hold at this temperature?

What is the relative humidity?

Calculations:

1b) The air temperature in a warehouse is measured and a dry-bulb reading of 30*°C* (86*°F*) is obtained. The amount of water vapor in the air is 21 *g*H2O/*kg*air.

What is the specific humidity?

What is the maximum amount of water vapor the air can hold at this temperature?

What is the relative humidity?

Calculations:

1c) The air temperature in the steam bath room of a food-processing plant is measured and a dry-bulb reading of 40*°C* (104*°F*) is obtained. The amount of water vapor in the air is 42 *g*H2O/*kg*air.

What is the specific humidity?

What is the maximum amount of water vapor the air can hold at this temperature?

What is the relative humidity?

Calculations:

2a) Following the correct use of a sling psychrometer, the dry-bulb temperature was found to be 16*°C* (60.8*°F*) and the wet bulb temperature was found to be 12*°C* (53.6*°F*).

What is the wet-bulb depression?

What is the relative humidity?

2b) Following the correct use of a sling psychrometer, the dry-bulb temperature was found to be 22*°C* (71.6*°F*) and the wet bulb temperature was found to be 13*°C* (55.4*°F*).

What is the wet-bulb depression?

What is the relative humidity?

2c) Following the correct use of a sling psychrometer, the dry-bulb temperature was found to be 27*°C* (80.6*°F*) and the wet bulb temperature was found to be 19*°C* (66.2*°F*).

What is the wet-bulb depression?

What is the relative humidity?

**Part II: Calculation of WBGT Index**

Temperature measurements were taken on a construction site during a clear, summer day. One employee was monitored during the performance of tasks during the hottest time of the day. The employee was engaged in tying off rebar, and took breaks in an air-conditioned trailer. The job-site supervisor insisted employees take a 15-minute break every 45 minutes and that they drink plenty of water or electrolyte supplement (e.g., Gatorade®).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Sample** | **Sampling****Period** | **Time****(min)** | **Area****Sampled** | **Activity** | **Readings from Heat Stress Monitor (in *°F*)** |
| ***Tg*** | ***Tdb*** | ***Tnw*b** | ***WGBT*** |
| 1 | 1:30 to 2:00 | 30 | Foundation Pit | Rebar tying – moderate work | 99 | 96 | 81 |  |
| 2 | 2:00 to 2:15 | 15 | Foundation Pit | Rebar tying – moderate work | 100 | 94 | 83 |  |
| 3 | 2:15 to 2:30 | 15 | Break Room | Break | 75 | 73 | 67 |  |
| 4 | 2:30 to 2:45 | 15 | Foundation Pit | Rebar tying – moderate work | 101 | 97 | 73 |  |
| 5 | 2:45 to 3:15 | 30 | Laydown Yard | Unloading/packing rebar – heavy work | 102 | 96 | 85 |  |
| 6 | 3:15 to 3:30 | 15 | Break Room | Break | 75 | 74 | 70 |  |

3a) Determine the *WBGT* for each sampling period. *(8 points)*

Formula(s): *and*

period 1: = =

period 2: = =

period 3: = =

period 4: = =

period 5: = =

period 6: = =

3b) Round each of the answers to the nearest whole number and record them in the table. *Note: Use these rounded figures for future calculations. (2 points)*

3c) Determine heat stress based on a two-hour time-weighted average. *(4 points)*

Formula:

Calculations: (*WBGT*1)(*t*1) = =

(*WBGT*2)(*t*2) = =

(*WBGT*3)(*t*3) = =

(*WBGT*4)(*t*4) = =

(*WBGT*5)(*t*5) = =

(*WBGT*6)(*t*6) = =

 total min = total =

=

= *(round to nearest tenth)*

3d) What work/rest regime and category does this individual fall under? *(1 pt.)*

3e) Has an overexposure occurred with this worker? *(1 point)*

Temperature measurements were taken on a logging site during a warm, clear day during the late spring. One employee was monitored during the performance of tasks during the hottest time of the day. The employee was working on a log landing, and took short, intermittent breaks by standing in the shade of a nearby tree.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Sample** | **Sampling****Period** | **Time****(min)** | **Area****Sampled** | **Activity** | **Readings from Heat Stress Monitor (in *°F*)** |
| ***Tg*** | ***Tdb*** | ***Tnw*b** | ***WGBT*** |
| 1 | 12:30 to 12:35 | 5 | Log Landing | Unhooking chokers – moderate work | 75 | 70 | 59 |  |
| 2 | 12:35 to 12:48 | 13 | Log Landing | Log limbing – heavy work | 75 | 71 | 57 |  |
| 3 | 12:48 to 12:51 | 3 | Standing in Shade | Break | 73 | 69 | 56 |  |
| 4 | 12:51 to 12:57 | 6 | Log Landing | Unhooking chokers – moderate work | 76 | 71 | 59 |  |
| 5 | 12:57 to 1:07 | 10 | Log Landing | Log limbing – heavy work  | 76 | 72 | 58 |  |
| 6 | 1:07 to 1:21 | 14 | Log Landing | Cutting logs to length – heavy work | 76 | 73 | 58 |  |
| 7 | 1:21 to 1:25 | 4 | Standing in Shade | Break | 74 | 70 | 56 |  |
| 8 | 1:25 to 1:32 | 7 | Log Landing | Unhooking chokers – moderate work | 77 | 72 | 60 |  |
| 9 | 1:32 to 1:43 | 11 | Log Landing | Log limbing – heavy work | 77 | 73 | 61 |  |
| 10 | 1:43 to 1:57 | 14 | Log Landing | Cutting logs to length – heavy work | 78 | 73 | 63 |  |
| 11 | 1:57 to 2:12 | 15 | Log Landing | Fueling/Sharpening Saw – light work | 78 | 74 | 62 |  |
| 12 | 2:12 to 2:30 | 18 | Log Landing | Piling Slash – very heavy work | 76 | 73 | 60 |  |

4a) Determine the *WBGT* for each sampling period. *(13 points)*

Formula:

period 1: = =

period 2: = =

period 3: = =

period 4: = =

period 5: = =

period 6: = =

period 7: = =

period 8: = =

period 9: = =

period 10: = =

period 11: = =

period 12: = =

4b) Round each of the answers to the nearest whole number and record them in the table. *Note: Use these rounded figures for future calculations.* *(3 points)*

4c) Determine heat stress based on a two-hour time-weighted average. *(29 points)*

Formula:

Calculations: (*WBGT*1)(*t*1) = =

(*WBGT*2)(*t*2) = =

(*WBGT*3)(*t*3) = =

(*WBGT*4)(*t*4) = =

(*WBGT*5)(*t*5) = =

(*WBGT*6)(*t*6) = =

(*WBGT*7)(*t*7) = =

(*WBGT*8)(*t*8) = =

(*WBGT*9)(*t*9) = =

(*WBGT*10)(*t*10) = =

(*WBGT*11)(*t*11) = =

(*WBGT*12)(*t*12) = =

 total min = total =

=

= *(round to nearest tenth)*

4d) What work/rest regime and category does this individual fall under? *(1 pt.)*

4e) Has an overexposure occurred with this worker? Explain. *(1 point)*

**Part III: Clothing Adjustment Factors**

Temperature measurements were taken at a hazardous waste cleanup site during a warm, clear day during the late spring. One employee was monitored during the performance of tasks during the hottest time of the day. The employee was engaged in working on spill cleanup, and took short, intermittent breaks by standing in the shade provided by an awning. Let us assume this individual performed tasks comparable in intensity to those performed by the logger in the previous example, and that all temperature conditions were identical to those experienced by the logger. The only difference is that the worker engaged in cleanup activities was wearing vapor-barrier coveralls (over cloth coveralls and with a hood, but without a respirator).

5a) What is the *WBGT* Clothing Adjustment Factor? *(1 point)*

5b) How did you determine the CAF? Show work. *(2 points)*

5c) Revise the original *WBGT*s. *Note: Use the original, unrounded, values to avoid potential compounding of errors).* *(12 points)*

 original *WBGT* CAF *WBGT* + CAF rounded to nearest

 whole number\*

period 1: + =

period 2: + =

period 3: + =

period 4: + =

period 5: + =

period 6: + =

period 7: + =

period 8: + =

period 9: + =

period 10: + =

period 11: + =

period 12: + =

*\*Note: Use these rounded values in future calculations.*

5d) Recalculate heat stress based on a two-hour time-weighted average. *(4 points)*

Formula:

Calculations: (*WBGT*1)(*t*1) = =

(*WBGT*2)(*t*2) = =

(*WBGT*3)(*t*3) = =

(*WBGT*4)(*t*4) = =

(*WBGT*5)(*t*5) = =

(*WBGT*6)(*t*6) = =

(*WBGT*7)(*t*7) = =

(*WBGT*8)(*t*8) = =

(*WBGT*9)(*t*9) = =

(*WBGT*10)(*t*10) = =

(*WBGT*11)(*t*11) = =

(*WBGT*12)(*t*12) = =

 total min = total =

=

= *(round to nearest tenth)*

What work-load category does this individual fall under? *(1 pt.)*

Has an overexposure occurred with this worker? Explain. *(1 point)*

**Part IV: Screen Levels for Heat Stress**

You are in charge of health and safety at a job site. For each of the following workplace scenarios, identify the action limit screening WBGT temperature (in *°F*) and the TLV screening temperature (in *°F*). *(10 points)*

 **Action Limit Screening TLV Screening**

continuous, light work

27% work/73% rest, very heavy work

48% work/52% rest, moderate work

76% work/24% rest, heavy work

17% work/83% rest, moderate work