The Case of the
OVERHEATED CONSTRUCTION WORKER

By Mitch Ricketts

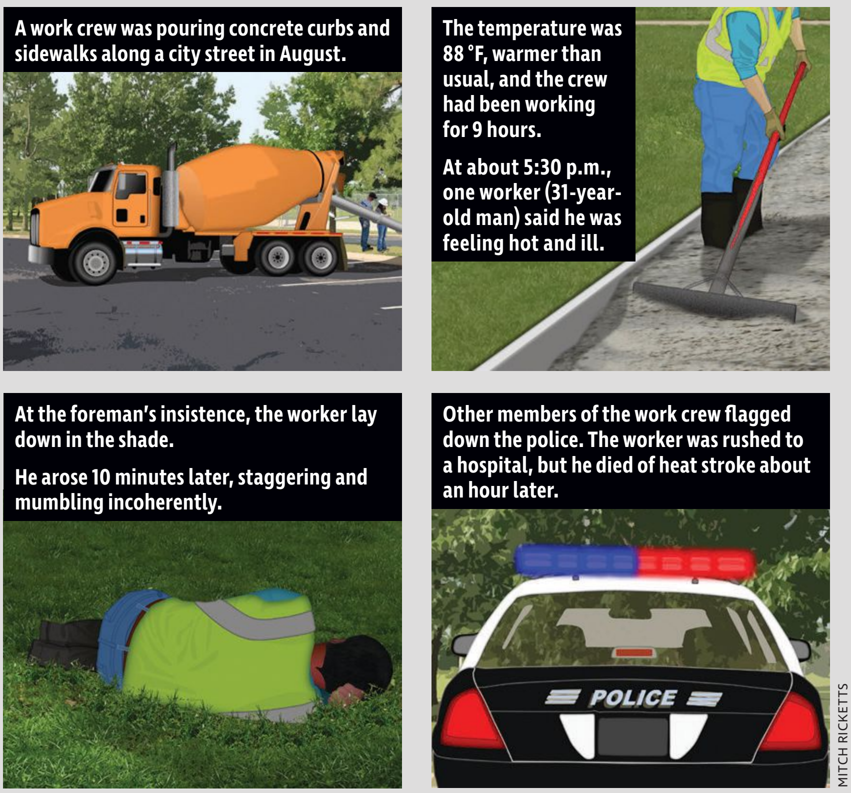
Math Toolbox is designed to help readers apply STEM principles to everyday safety issues. Many readers may feel apprehensive about math and science. This series employs various communication strategies to make the learning process easier and more accessible.

Overexposure to extreme heat may lead to heat exhaustion, heat stroke, dehydration, kidney damage and even death (Flouris, Dinas, Ioannou et al., 2018; Park, Kim & Oh, 2017). Figure 1 illustrates how quickly the effects of heat can turn tragic in the workplace. In this case, a worker had labored for 9 hours during higher-than-average temperatures. When unmistakable signs of overheating finally became evident to others, his condition had deteriorated to the extent that he could not be saved.

Safety professionals are often asked to specify how much heat is excessive. The answer to this question is not based solely on air temperature because heat-related illnesses occur when warm temperatures combine with other factors such as high relative humidity, lack of shade, absence of cooling breezes, strenuous work duties, heavy clothing and personal factors such as inadequate acclimatization (Flouris et al., 2018; Park et al., 2017).

Instead of relying on air temperature alone, we normally assess the potential for heat stress by considering relevant workplace conditions in conjunction with a measure of environmental factors known as the wet-bulb globe temperature index (WBGT). WBGT is useful because it combines the effects of several important environmental factors into a single measure that is known to predict heat-related illnesses (NIOSH, 2016).

FIGURE 1
HEAT STROKE, MINNESOTA



Note. Adapted from "Construction Worker Dies From Heat Stroke (MN FACE Investigation 93MN00901)," by NIOSH, 1993.

Heat Stress Concepts

The most severe heat-related illnesses occur when the body generates and absorbs heat faster than it can be dissipated (NIOSH, 2016). Processes involved in the generation and absorption of heat are encompassed in the term *heat stress*.

Heat stress is the stress represented by the combined effects of metabolic heat, clothing and the environmental factors that are reflected in WBGT. Metabolic heat is a by-product of ordinary cell metabolism, muscle activity and other internal (bodily) processes. Metabolic heat increases during vigorous work activity and decreases during periods of rest. Clothing affects heat stress by limiting the escape of heat from the body.

While the concept of heat stress includes sources of heat and impediments to cooling, the term *heat strain* describes the body's physiological responses to heat stress. Heat strain occurs as the body attempts to maintain a safe and stable body temperature. Excessive heat strain may be indicated by profuse sweating, rapid heart rate and elevated core body temperature. Over time, our bodies may become trained to better tolerate heat exposure through a gradual process known as acclimatization.

During acclimatization, the body becomes more efficient at maintaining a safe and stable core temperature. Workers become acclimatized by steadily increasing their work time in hot environments over several days. Acclimatized workers are less likely to suffer heat illnesses compared to workers who have not been acclimatized.

Environmental factors most relevant to heat stress are typically measured as dry-bulb temperature, natural wet-bulb temperature and black-globe temperature (Figures 2 and 3). Dry-bulb temperature (DB) is the temperature of the ambient air, measured with an ordinary thermometer. Although dry-bulb temperature may predict the comfort of sedentary workers in conditioned office environments, it has limited use for predicting heat-related illnesses when work rate, relative humidity or radiant heat are extreme.

Natural wet-bulb temperature (WB) is often measured with a thermometer covered by a wick (such as wet gauze) exposed

FIGURE 2
TEMPERATURE MEASURES

Dry bulb temperature (DB) is a measure of air temperature. Natural wet bulb temperature (WB) incorporates the thermal effects of evaporative cooling. Black globe temperature (GT) adds the impact of radiant heat.

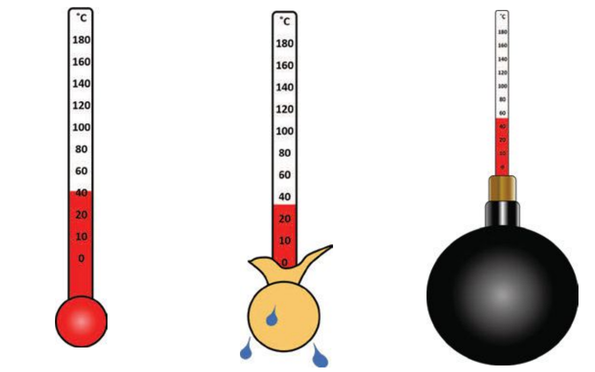


FIGURE 3
WBGT MONITOR

WBGT monitor (left). Close-up of sensors (right).

Note. Photos copyright 2020 by TSI Inc. Reprinted with permission.

to natural air movement. Natural wet-bulb temperatures tend to be elevated when both relative humidity and air temperature are high. Elevated natural wet-bulb temperature is an important predictor of heat-related illnesses because it suggests perspiration may not evaporate fast enough to remove heat from a worker's body.

Black-globe temperature (GT) is typically measured by placing a thermometer in the air space within a blackened copper shell. The globe may be exposed to radiant heat sources (such as the sun) in a manner that represents worker exposures to radiant heat.

Wet-bulb globe temperature index (WBGT) combines the measures of natural wet-bulb temperature, black-globe temperature and (in some situations) dry-bulb temperature into a single index to estimate heat stress when the effects of other factors such as work rate and clothing are also known (Figure 3). WBGT is interpreted in each workplace based on guidelines issued by NIOSH (2016) or other organizations such as American Conference of Governmental Industrial Hygienists (ACGIH, 2020). WBGT is calculated in either of two ways, depending on whether workers are exposed to heat from the sun. For both equations, we may use temperature units in Celsius, Kelvin, Fahrenheit or Rankin, as long as we maintain consistency throughout the calculations.

For outdoor settings when workers are exposed to solar radiation, the equation is:

$$WBGT = (0.7 \cdot WB) + (0.2 \cdot GT) + (0.1 \cdot DB)$$
(outdoors with solar heat load)

For indoor settings, or outdoors with no solar heat load, the equation is:

$$WBGT = (0.7 \cdot WB) + (0.3 \cdot GT)$$
(indoors, or outdoors with no solar heat load)

where:
WBGT = wet-bulb globe temperature index

WB = natural wet-bulb temperature, reflecting effects of evaporative cooling and air temperature

GT = black-globe temperature, reflecting effects of radiant heat and air temperature

DB = dry-bulb temperature, reflecting effects of air temperature alone

Note: Be sure to use the same temperature metric (e.g., °C, °K, °F or °R) to express variables WB, GT and DB throughout the equation. The resulting WBGT index will then be expressed in the same metric as the variables you enter.

Calculating WBGT: Outdoors, With Solar Heat Load

Detailed environmental conditions were not recorded in the case that introduced our topic, so we will calculate WBGT using hypothetical values. With that in mind, imagine a worker is laboring outdoors, at a moderate work rate, with exposure to solar radiation (sunshine). Further imagine that the worker is wearing a conventional one-layer work clothing ensemble that includes a long-sleeved work shirt and trousers. Finally, imagine we measure the following temperatures throughout an 8-hour workday:

- Natural wet-bulb temperature is measured as 80 °F. This is the value of WB in the formula for WBGT.
- Black-globe temperature is measured as 98 °F. This is the value of GT in the formula.
- Dry-bulb temperature is measured as 88 °F. This is the value of DB in the formula.

Based on these measurements, we can calculate the wet-bulb globe temperature index (WBGT) in °F as follows:

Step 1: Start with the equation for WBGT, outdoors with solar heat load:

$$WBGT = (0.7 \cdot WB) + (0.2 \cdot GT) + (0.1 \cdot DB)$$
(outdoors with solar heat load)

Step 2: Insert the known values for natural wet-bulb temperature (WB = 80 °F), black-globe temperature (GT = 98 °F) and dry-bulb temperature (DB = 88 °F). Then solve for WBGT:

$$WBGT = (0.7 \cdot 80) + (0.2 \cdot 98) + (0.1 \cdot 88) = 84.4\,°F$$
(outdoors with solar heat load)

Step 3: Our calculation indicates the WBGT is 84.4 °F. To interpret our result, we'll refer to the NIOSH (2016) revised criteria document for occupational exposure to heat and hot environments. Our hypothetical problem indicated the worker was laboring at a moderate work rate, wearing a conventional one-layer work clothing ensemble with a long-sleeved work shirt and trousers. Table 1 (p. 65) is adapted from the NIOSH (2016) revised criteria document. For a WBGT of 84.4 °F and a moderate work rate, Table 1 recommends a water intake of about 0.75 quarts per hour and 50 minutes of actual work for every 10 minutes of rest in the shade per hour (with variations in fluid intake as discussed in the table notes).

To keep our calculations manageable, we will focus on requirements for water and rest. A future article will explore additional NIOSH recommendations for heat exposure, including the recommended alert limit (RAL) for non-acclimatized workers and the recommended exposure limit (REL) for acclimatized workers.

Alternate example: Let's calculate WBGT for a different example, this time using the Celsius scale. Imagine a worker is laboring at an easy work rate outdoors with exposure to the sun. Again, the worker is wearing a conventional one-layer work clothing ensemble with a long-sleeved work shirt and trousers. This time, imagine the natural wet-bulb temperature is 32 °C, the black-globe temperature is 42 °C and the dry-bulb temperature is 37 °C. What is the wet-bulb globe temperature index in °C?

To solve in degrees Celsius, we use the original equation:

$$WBGT = (0.7 \cdot WB) + (0.2 \cdot GT) + (0.1 \cdot DB)$$
(outdoors with solar heat load)

We then insert the new values for natural wet-bulb temperature (WB = 32 °C), black-globe temperature (GT = 42 °C) and dry-bulb temperature (DB = 37 °C) to obtain the following result:

$$WBGT = (0.7 \cdot 32) + (0.2 \cdot 42) + (0.1 \cdot 37) = 34.5\ °C$$
(outdoors with solar heat load)

To interpret the WBGT index of 34.5 °C using Table 1, we'll need to convert from Celsius to Fahrenheit using the following conversion equation:

$$°F = °C \cdot 1.8 + 32$$

Inserting our value of 34.5 °C, we obtain:

$$°F = 34.5 \cdot 1.8 + 32 = 94.1\ °F$$

After converting to Fahrenheit, we find the WBGT of 34.5 °C is equivalent to a WBGT of 94.1 °F. For an easy work rate, a conventional one-layer work clothing ensemble and a WBGT > 90 °F, Table 1 indicates the recommended water intake is about 1 quart per hour, with 50 minutes of actual work for every 10 minutes of rest in the shade per hour.

You Do the Math

Apply your knowledge to the following questions. Answers are on p. 70.

1) Outdoors, with a solar heat load, the natural wet-bulb temperature is 28 °C, the black-globe temperature is 44 °C and the dry-bulb temperature is 37 °C. Answer the following:

a) What is the wet-bulb globe temperature index (WBGT) in °C?

b) What is the value of this WBGT when converted to °F?

c) For a moderate work rate and a conventional one-layer work clothing ensemble, what is the recommended water intake and work/rest regimen according to Table 1?

2) Outdoors, with a solar heat load, the natural wet-bulb temperature is 94 °F, the black-globe temperature is 118 °F and the dry-bulb temperature is 104 °F. Answer the following:

a) What is the wet-bulb globe temperature index (WBGT) in °F?

b) For an easy work rate and a conventional one-layer work clothing ensemble, what is the recommended water intake and work/rest regimen according to Table 1?

Calculating WBGT: Indoors (or Outdoors With No Solar Heat Load)

Our previous calculations assumed workers were laboring outdoors with exposure to the sun. Our calculations will be modified slightly when workers are located indoors or have no exposure to solar radiation. In these cases, we use a modified WBGT formula that omits the dry-bulb temperature and increases the weighting of the black-globe temperature:

$$WBGT = (0.7 \cdot WB) + (0.3 \cdot GT)$$
(indoors, or outdoors with no solar heat load)

where:
WBGT = wet-bulb globe temperature index
WB = natural wet-bulb temperature, reflecting effects of evaporative cooling and air temperature
GT = black-globe temperature, reflecting effects of radiant heat and air temperature

Note: Again, be sure to use the same temperature metric (e.g., °C, °K, °F or °R) to express variables WB and GT throughout the equation. This ensures that the resulting WBGT index is expressed in the same metric as the variables you enter.

Let's imagine a worker is laboring indoors, at a moderate work rate, wearing a conventional one-layer work clothing ensemble that includes a long-sleeved work shirt and trousers. The worker is exposed to the following temperatures throughout an 8-hour workday:

• Natural wet-bulb temperature is measured as 81 °F. This is the value of WB in the formula.
• Black-globe temperature is measured as 85 °F. This is the value of GT.
• Since the worker has no exposure to solar radiation, we do not include any value for dry-bulb temperature.

Based on these measurements, we can calculate the wet-bulb globe temperature index (WBGT) in °F as follows:

Step 1: Start with the equation for WBGT, indoors (or outdoors with no solar heat load):

$$WBGT = (0.7 \cdot WB) + (0.3 \cdot GT)$$
(indoors, or outdoors with no solar heat load)

Step 2: Insert the known values for natural wet-bulb temperature (WB = 81 °F) and black-globe temperature (GT = 85 °F). Then solve for WBGT (indoors, or outdoors with no solar heat load):

$$WBGT = (0.7 \cdot 81) + (0.3 \cdot 85) = 82.2\ °F$$
(indoors, or outdoors with no solar heat load)

Step 3: Our calculation indicates the WBGT is 82.2 °F. For a moderate work rate and a conventional one-layer work clothing ensemble and a WBGT of 82.2 °F, Table 1 indicates the recommended water intake is about 0.75 quarts per hour, with 50 minutes of actual work for every 10 minutes of rest in the shade per hour.

Alternate example: This time, let's calculate WBGT using the Celsius scale for a different example in which a worker is laboring indoors, at a hard work rate, wearing a conventional one-layer work clothing ensemble with a long-sleeved work shirt and trousers. Imagine the natural wet-bulb temperature (WB) is 26 °C and the black-globe temperature (GT) is 29 °C. What is the wet-bulb globe temperature index (WBGT) in °C?

To solve in degrees Celsius, we use the equation for indoor conditions:

$$WBGT = (0.7 \cdot WB) + (0.3 \cdot GT)$$
(indoors, or outdoors with no solar heat load)

We then insert the new values for natural wet-bulb temperature (WB = 26 °C) and black-globe temperature (GT = 29 °C) to obtain the following result:

$$WBGT = (0.7 \cdot 26) + (0.3 \cdot 29) = 26.9\ °C$$
(indoors, or outdoors with no solar heat load)

To interpret the WBGT index of 26.9 °C using Table 1, we'll need to convert from Celsius to Fahrenheit:

$$°F = °C \cdot 1.8 + 32$$

Inserting our value of 26.9 °C, we obtain:

$$°F = 26.9 \cdot 1.8 + 32 = 80.42\ °F$$

After converting to Fahrenheit, we find the WBGT of 26.9 °C is equivalent to a WBGT of 80.42 °F. For a hard work rate, a conventional one-layer work clothing ensemble and a WBGT of 80.42 °F, Table 1 indicates the recommended water intake is about 0.75 quart per hour, with 40 minutes of actual work for every 20 minutes of rest in the shade per hour.

You Do the Math

Apply your knowledge to the following questions. Answers are on p. 70.

3) Indoors (or outdoors, with no solar heat load), the natural wet-bulb temperature is 84 °F and the black-globe temperature is 91 °F. Answer the following:

a) What is the wet-bulb globe temperature index (WBGT) in °F?

b) For a moderate work rate and a conventional one-layer work clothing ensemble, what is the recommended water intake and work/rest regimen according to Table 1?

4) Indoors (or outdoors, with no solar heat load), the natural wet-bulb tempera-

TABLE 1

NIOSH RECOMMENDATIONS FOR FLUID REPLACEMENT & REST DURING WARM WEATHER CONDITIONS

	Easy work (250 W)		Moderate work (425 W)		Hard work (600 W)	
WBGT index (°F)	Work/rest (min)	Water intake[a] (qt·h^{-1})	Work/rest (min)	Water intake (qt·h^{-1})	Work/rest (min)	Water intake (qt·h^{-1})
78 to 81.9	Unlimited	0.5	Unlimited	0.75	40/20	0.75
82 to 84.9	Unlimited	0.5	50/10	0.75	30/30	1.0
85 to 87.9	Unlimited	0.75	40/20	0.75	30/30	1.0
88 to 89.9	Unlimited	0.75	30/30	0.75	20/40	1.0
90+	50/10	1.0	20/40	1.0	10/50	1.0

Note: Rest = sitting or standing, in the shade if possible. Adapted from Table 8-1, "Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments (Revised Criteria 2016)," by NIOSH, 2016.
[a]Fluid needs can vary on the basis of individual differences (± 0.25 qt·h^{-1}) and exposure to full sun or full shade (± 0.25 qt·h^{-1}). Fluid intake should not exceed 1.5 qt·h^{-1}; daily fluid intake generally should not exceed 12 quarts. This is not to suggest limiting fluid intake by highly conditioned persons, who may require greater than 12 quarts daily.

ture is 27 °C and the black-globe temperature is 33 °C. Answer the following:

a) What is the wet-bulb globe temperature index (WBGT) in °C?

b) What is the value of this WBGT when converted to °F?

c) For a hard work rate and a conventional one-layer work clothing ensemble, what is the recommended water intake and work/rest regimen according to Table 1?

How Much Have I Learned?

Try the problems on your own. Answers are on p. 70.

5) Outdoors, with a solar heat load, the natural wet-bulb temperature is 86 °F, the black-globe temperature is 96 °F and the dry-bulb temperature is 92 °F. Answer the following:

a) What is the wet-bulb globe temperature index (WBGT) in °F?

b) For an easy work rate and a conventional one-layer work clothing ensemble, what is the recommended water intake and work/rest regimen according to Table 1?

6) Indoors (or outdoors, with no solar heat load), the natural wet-bulb temperature is 79 °F and the black-globe temperature is 87 °F. Answer the following:

a) What is the wet-bulb globe temperature index (WBGT) in °F?

b) For a hard work rate and a conventional one-layer work clothing ensemble, what is the recommended water intake and work/rest regimen according to Table 1?

7) Imagine a different scenario in which we measure in Celsius and obtain a WBGT of 32 °C. Convert to °F.

The Language of Heat Stress

Readers will encounter the following concepts in codes, certification exams and conversations with other professionals. Match the numbered concepts with their paraphrased definitions (lettered). All concepts have been defined in the text, formulas and illustrations. Answers are on p. 70.

Concepts

8) acclimatization
9) black-globe temperature (GT)
10) dry-bulb temperature (DB)
11) heat strain
12) heat stress
13) metabolic heat
14) natural wet-bulb temperature (WB)
15) wet-bulb globe temperature index (WBGT)

Definitions (in random order)

a) Body's physiological response to heat stress, occurring as the body attempts to maintain a safe and stable body temperature.

b) Heat that is a by-product of ordinary cell metabolism, muscle activity and other internal (bodily) processes.

c) Measure that combines natural wet-bulb temperature, black-globe temperature and (in some situations) dry-bulb temperature into a single index to estimate heat stress when the effects of other factors such as workload and clothing are also known.

d) Physiological "training" process during which the body becomes more efficient at maintaining a safe and stable core temperature.

e) Temperature of the ambient air; measured with an ordinary thermometer.

f) Temperature that incorporates the effects of exposure to radiant heat sources as well as air temperature; measured by placing a thermometer in the air space within a blackened copper shell.

g) Temperature that incorporates the effects of evaporative cooling as well as air temperature; measured with a thermometer covered by a wick exposed to natural air movement.

h) Stress represented by the combined effects of metabolic heat, clothing and the environmental factors that are reflected in WBGT.

For Further Study

•*ASSP's ASP Examination Prep: Program Review and Exam Preparation*, edited by Joel M. Haight, 2016.

•*OSHA Technical Manual* (TED 01-00-015), Section III, Chapter 4: Heat stress, by OSHA, 2013; **www.osha.gov/dts/osta/otm/otm_iii/otm_iii_4.html**. **PSJ**

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employees in the safety area while training and educating them to take ownership at their level and provide input. Operationally, we need to be part of the team while remaining observers at times so that the team can function effectively in our absence. Therefore, employees serving on the ERT must have ownership and support. It is not your team, it is theirs.

Create an ERT operations manual (separate from the EAP) to provide policies and rules for the team as standards of operation. This manual should include a mission statement, created by the team, and should address attendance policy, meetings, training requirements, and other factors in how the team will function and sustain itself. These standards of operation will allow the team to function without the emergency manager on site.

Also important is understanding the metrics surrounding the ERT, for example, how many calls the team responds to each month or year (Figure 4, p. 69). This can help to demonstrate the team's value, as well as maintain active support of the team with equipment and training. First responder care can help employees heal faster, reduce recordable injuries and get employees back to work sooner. It is amazing what ice can do for an injury, as well as how the employees feel when they are being taken care of.

Although members of this team will not receive additional pay, they receive training and other benefits, such as T-shirts, hats and vests. But their volunteer service should not go without gratitude. A simple "thank you" in the form of movie tickets, lunches or other gestures can go a long way to keep team members motivated.

Conclusion

Following the best practices outlined in this article, an organization can properly develop a sustainably active ERT. Team members who receive annual training and attend monthly meetings gain confidence when responding and providing patient care. Whether an organization has an established ERT or is just beginning to develop one, this framework can help an organization assess the team's current state and where it needs to go. Being prepared for any emergency requires leadership that recognizes the value of the team and provides the needed support for training, equipment, meeting attendance and taking command to propel the ERT to the next level. **PSJ**

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Math Toolbox, continued from pp. 62-65

Answers: The Case of the Overheated Construction Worker

You Do the Math

Your answers may vary slightly due to rounding.

1a) $WBGT = (0.7 \cdot 28) + (0.2 \cdot 44) + (0.1 \cdot 37) = 32.1\,°C$ (outdoors with solar heat load)

1b) $°F = 32.1 \cdot 1.8 + 32 = 89.78\,°F$

1c) According to Table 1, for a moderate work rate, conventional one-layer work clothing ensemble and WBGT of 89.78 °F, the recommended water intake is about 0.75 quarts of water per hour and the recommended work/rest regimen is 30 minutes of actual work for every 30 minutes of rest in the shade per hour.

2a) $WBGT = (0.7 \cdot 94) + (0.2 \cdot 118) + (0.1 \cdot 104) = 99.8\,°F$ (outdoors with solar heat load)

2b) According to Table 1, for an easy work rate, conventional one-layer work clothing ensemble and WBGT of 99.8 °F, the recommended water intake is about 1.0 quart of water per hour and the recommended work/rest regimen is 50 minutes of actual work for every 10 minutes of rest in the shade per hour.

3a) $WBGT = (0.7 \cdot 84) + (0.3 \cdot 91) = 86.1\,°F$ (indoors, or outdoors with no solar heat load)

3b) According to Table 1, for a moderate work rate, conventional one-layer work clothing ensemble and WBGT of 86.1 °F, the recommended water intake is about 0.75 quarts of water per hour and the recommended work/rest regimen is 40 minutes of actual work for every 20 minutes of rest in the shade per hour.

4a) $WBGT = (0.7 \cdot 27) + (0.3 \cdot 33) = 28.8\,°C$ (indoors, or outdoors with no solar heat load)

4b) $°F = 28.8 \cdot 1.8 + 32 = 83.84\,°F$

4c) According to Table 1, for a hard work rate, conventional one-layer work clothing ensemble and WBGT of 83.84 °F, the recommended water intake is about 1 quart of water per hour and the recommended work/rest regimen is 30 minutes of actual work for every 30 minutes of rest in the shade per hour.

How Much Have I Learned?

5a) $WBGT = (0.7 \cdot 86) + (0.2 \cdot 96) + (0.1 \cdot 92) = 88.6°F$ (outdoors with solar heat load)

5b) According to Table 1, for an easy work rate, conventional one-layer work clothing ensemble and WBGT of 88.6 °F, the recommended water intake is about 0.75 quarts of water per hour with an unlimited work/rest regimen (i.e., no rest breaks required).

6a) $WBGT = (0.7 \cdot 79) + (0.3 \cdot 87) = 81.4\,°F$ (indoors, or outdoors with no solar heat load)

6b) According to Table 1, for a hard work rate, conventional one-layer work clothing ensemble and WBGT of 81.4 °F, the recommended water intake is about 0.75 quarts of water per hour and the recommended work/rest regimen is 40 minutes of actual work for every 20 minutes of rest in the shade per hour.

7) $°F = 32 \cdot 1.8 + 32 = 89.6\,°F$

The Language of Heat Stress

8) d; 9) f; 10) e; 11) a; 12) h; 13) b; 14) g; 15) c.