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Heat Index and Adjusted Temperature as Surrogates for Wet Bulb Globe Temperature to Screen for Occupational Heat Stress

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Ambient temperature and relative humidity are readily available and thus tempting metrics for heat stress assessment. Two methods of using air temperature and relative humidity to create an index are Heat Index and Adjusted Temperature. The purposes of this article are: (1) to examine how well Heat Index and Adjusted Temperature estimated the wet bulb globe temperature (WBGT) index, and (2) to suggest how Heat Index and Adjusted Temperature can be used to screen for heat stress level. Psychrometric relationships were used to estimate values of actual WBGT for conditions of air temperature, relative humidity, and radiant heat at an air speed of 0.5 m/s. A relationship between Heat Index [°F] and WBGT [°C] was described by WBGT = −0.0034 HI² + 0.96 HI – 34. At lower Heat Index values, the equation estimated WBGTs that were ±2°C-WBGT around the actual value, and to about ±0.5°C-WBGT for Heat Index values > 100°F. A relationship between Adjusted Temperature [°F] and WBGT [°C] was described by WBGT = 0.45 Tadj – 16. The actual WBGT was between 1°C-WBGT below the estimated value and 1.4°C-WBGT above. That is, there was a slight bias toward overestimating WBGT from Adjusted Temperature. Heat stress screening tables were constructed for metabolic rates of 180, 300, and 450 W. The screening decisions were divided into four categories: (1) < alert limit, (2) < exposure limit, (3) hourly time-weighted averages (TWAs) of work and recovery, and (4) a caution zone for an exposure > exposure limit at rest. The authors do not recommend using Heat Index or Adjusted Temperature instead of WBGT, but they may be used to screen for circumstances when a more detailed analysis using WBGT is appropriate. A particular weakness is accounting for radiant heat; and neither air speed nor clothing was considered.

Keywords adjusted temperature, heat index, heat stress, WBGT

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INTRODUCTION

The job risk factors for heat stress are the ambient environment, metabolic rate, and clothing. Wet bulb globe temperature (WBGT) is a commonly used index for the environmental conditions and WBGT-based occupational exposure limits (OELs) are adjusted for metabolic rate and clothing.[1–4] The OELs based on WBGT were designed so that most workers can sustain the heat stress for long periods of time. For instance, Lind[5,6] showed that 14 subjects working near the upper sustainable limit could sustain the heat stress exposure; that is, maintain a thermal equilibrium for 8 hours. This observation also means that many workers can safely work at higher levels. In this regard, the WBGT-based OELs are protective.

WBGT is a common metric and has the same relationship between dry bulb temperature and water vapor pressure as the upper limit of sustainable exposures to heat stress,[7] which means that it is a robust index for exposure assessment. We have observed that practitioners often look for a surrogate measure of WBGT that appears to be more ready accessible. This search started in the late 1970s [8,9] and the interest has continued up to recent years.[10,11] For instance, the National Oceanographic and Atmospheric Administration (NOAA) promotes the Heat Index through the National Weather Service (NWS) advisories. The Occupational Safety and Health Administration (OSHA) provides some exposure guidance based on Heat Index.[12] Heat Index is also used in epidemiological studies, such as a recent paper for agricultural workers in Washington state,[13] because of its availability from weather service archives. Heat Index could be useful when the relationship with heat stress is established for a given location.[14] In general, Heat Index does not account for air speed and radiant heat, and most recommendations are not adjusted for metabolic rate or clothing.

In its recent draft for a revised criteria document for occupational heat stress, the National Institute for Safety and Health (NIOSH) included Adjusted Temperature as a method to assess the environmental contribution to heat stress (see Table 6-2 in the draft criteria document).[4] While the origin of the table is uncertain, the approach might have some utility. This table uses a reference condition of 30% relative humidity and no radiant heat, and increasing heat stress is associated with increasing air temperature. The Adjusted Temperature is then determined by changing the air temperature by a fixed amount depending on relative humidity and radiant heat. It does not consider air speed. The table recognizes the need for thresholds based on metabolic rate. Whether or not this table is published in the final version of the criteria document, it became available for use and thus was worth considering.

WBGT gained acceptance as an index of the environment because it accounts for air temperature, humidity, air speed, and radiant heat, all of which are important in understanding the heat exchange between a person and the environment. Because Heat Index considers only air temperature and humidity and Adjusted Temperature considers air temperature and humidity with a gross estimate of radiant heat, they cannot perform as well as WBGT in heat stress analyses. So, at best, they might be useful screening tools but not acceptable analysis tools for occupational hygiene practice.

The purpose of this article is to: (1) examine the ability of Heat Index and Adjusted Temperature to estimate WBGT, and (2) suggest a framework for using Heat Index and Adjusted Temperature to screen for heat stress level. Results also can be used to interpret data from epidemiological studies that report Heat Index.

METHODS

Psychrometrics

Because Heat Index and Adjusted Temperature use air (dry bulb) temperature and relative humidity, they are relatively easy to determine from meteorological data. The Adjusted Temperature does require an estimate of the radiant heat that is based on observation (e.g., direct sunlight). WBGT, however, is not easily estimated from meteorological data and requires the use of psychrometric relationships, thermodynamic models, and/or empirical relationships.[8–11,15–18] For this study, a set of user-defined functions for Excel (Microsoft, Redmond, Washington) used the relationships described by Bernard and Pourmoghani.[16]

First, water vapor pressure (Pv) [kPa] was determined from dry bulb temperature (Tdb) [°C] and percent relative humidity (rh):

$$\mathrm{Pv} = (\mathrm{rh}/100\%) * 0.6105 * \exp(17.27 * \mathrm{Tdb}/ \times(\mathrm{Tdb} + 237.3)) \quad (1)$$

Then psychrometric wet bulb temperature (Tpwb) [°C] was determined iteratively by solving the following equation where Pv and Tdb are known and trial values of Tpwb are used to find the value where both sides of the equation are the same value within 0.01 kPa:

$$\mathrm{Pv} = 0.6105 * \exp[17.27 * \mathrm{Tpwb}/(\mathrm{Tpwb} + 237.3)] - 0.067 * (\mathrm{Tdb} - \mathrm{Tpwb}) \quad (2)$$

Natural wet bulb temperature depends on air speed[16,17] so air speed was assumed to be low at 0.5 m/s. In the absence of radiant heat (Tg – Tdb < 4°C),[16]

$$\mathrm{Tnwb} = \mathrm{Tdb} - 0.94 * (\mathrm{Tdb} - \mathrm{Tpwb}) \quad (3)$$

The adjustments required for radiant heat were those described previously.[16] For air speed equal 0.5 m/s and radiant heat (Tg – Tdb > 4°C),

$$\mathrm{Tnwb} = \mathrm{Tpwb} + 0.25 * (\mathrm{Tg} - \mathrm{Tdb}) \quad (4)$$

As a reminder, WBGT has two formulations, which depend on whether the assessment is made under conditions of direct exposure to sunlight (WBGTout) or under conditions of shade or indoors (WBGTin).[1] Because direct sunlight raises the globe temperature to a greater extent compared to the effect it has on radiant heat load on a person, the weighting factor for globe temperature in direct sun is reduced from 0.3 to 0.2:

$$\mathrm{WBGTout} = 0.7\ \mathrm{Tnwb} + 0.2\ \mathrm{Tg} + 0.1\mathrm{Tdb} \quad (5)$$

$$\mathrm{WBGTin} = 0.7\ \mathrm{Tnwb} + 0.3\ \mathrm{Tg} \quad (6)$$

Heat Index

As originally proposed by Steadman,[19] what is now called Heat Index was a rational model that matched conditions of air temperature and humidity with other factors that affect heat exchange held constant. Anderson examined the performance of 21 methods to calculate Heat Index [°F] via equations and concluded that they were all satisfactory.[20] The method of Rothfusz of the NWS with some adjustments was used,[20,21] where temperature (T, °F) and relative humidity (R,%) are the inputs:

$$\begin{aligned}\text{Heat Index} = {} & -42.379 + 2.04901523\ \mathrm{T} + 10.14333127\ \mathrm{R} \\ & -0.22475541\ \mathrm{TR} - 0.00683783\ \mathrm{T}^2 \\ & -0.05481717\ \mathrm{R}^2 + 0.00122874\ \mathrm{T}^2\mathrm{R} \\ & +0.00085282\ \mathrm{TR}^2 - 0.00000199\ \mathrm{T}^2\ \mathrm{R}^2 \\ & +\mathrm{ADJ} \end{aligned} \quad (7)$$

where,

$$\begin{aligned}\mathrm{ADJ} = {} & 0 \text{ unless (1) } \mathrm{R} < 13\% \text{ and T is between 80 and112 °F,} \\ & \text{then } \mathrm{ADJ} = -[(13 - \mathrm{R})/4] * \mathrm{SQRT}([17 - \mathrm{ABS} \\ & \times(\mathrm{T} - 95.)]/17); \text{ or(2) if } \mathrm{R} > 85\% \text{ and T is between} \\ & \text{80 and 87°F, then } \mathrm{ADJ} = [(\mathrm{R} - 85)/10] \\ & *[(87 - \mathrm{T})/5] \end{aligned} \quad (8)$$

Heat Index values above 137°F and below 80°F were treated as out of range and not used in any analysis of data.

Adjusted Temperature

As presented in Table 6-2 in the draft NIOSH criteria document,[4] Adjusted Temperature (Tadj) appeared to be a surrogate measure of WBGT. The table also included exposure decisions depending on metabolic rate category. While the American Conference of Governmental Industrial Hygienists (ACGIH®) was cited as the source, there was not enough information to find it. Because Adjusted Temperature can be treated as a surrogate measure of environment, it should trace back to WBGT, which is the environmental index for the NIOSH Recommended Exposure Limit (REL).[3,4]

TABLE I. Adjustments [°F and°C] to Ambient Dry Bulb (air) Temperature for Relative Humidity [%] and Radiant Heat Level[A]

Condition	NIOSH 2013 Draft Criteria Document, Table 6-2	Recommended Adjustments	
Relative Humidity [%] - RHadj	[°F]	[°F]	[°C]
10	−8	−11	−6.1
20	−4	−5	−2.8
30 (Reference)	0	0	0
40	3	4	2.2
50	6	7	3.9
60	9	9	5.0
Radiant Heat - GTadj[B]	[°F]	[°F]	[°C]
None (Reference)	0	0	0
Low (WBGTin)	7	2	1.1
Low (WBGTout)		2	1.1
High (WBGTin)	13	6	3.3
High (WBGTout)		4	2.2
Mean Difference from Reference ± Standard Deviation [°C-WBGT]	−1.9 ± 2.2	0.1 ± 0.4	

[A] as described in the NIOSH draft criteria document[4] and as proposed in this article.
[B] Low Radiant Heat: Tg = Tdb + 7°F (or 3.9 C) and High Radiant Heat: Tg = Tdb + 13°F (or 7.2°C)

Adjusted Temperature depends on adjustments for relative humidity (RHadj) and radiant heat reflected in an increase in globe temperature above the air temperature (GTadj). Values for RHadj and GTadj are provided in Table I. Then,

$$\text{Tadj} = \text{Tair} + \text{RHadj} + \text{GTadj} \tag{9}$$

To estimate WBGT, the Adjusted Temperature equation was re-arranged as

$$\text{Tair} = \text{Tadj} - \text{Rhadj} - \text{GTadj} \tag{10}$$

and

$$\text{Tg} = \text{Tair} + \text{GTadj} \tag{11}$$

Then WBGTin and WBGTout were estimated from dry bulb (air) temperature, relative humidity, and globe temperature as described under Psychrometrics previously.

There were 18 scenarios (6 levels of relative humidity and 3 levels of radiant heat) over a range of Adjusted Temperatures from 90 to 112°F in 1°F increments (23 temperatures). Using the reference conditions as the 23 temperatures at 30% relative humidity and no radiant heat, differences in WBGT from the reference could be determined for the remaining 17 scenarios. The mean and standard deviation of the 391 differences was calculated to represent any overall bias in using adjustments in Table I and the degree of variation.

A relatively simple process was used to reduce the overall bias and variance. First, the no radiant heat condition was used to find a whole number adjustment in °F for a given relative humidity that would be the closest to no difference in WBGT from the reference based on the average of the 23 conditions. Once the relative humidity adjustments were selected, then the same approach was taken for a selected radiant heat adjustment for low and then for high radiant heat.

Screening Tables

In addition to using Heat Index or Adjusted Temperature as a surrogate for WBGT, NIOSH draft criteria document Table 6-2 provided a framework for exposure decisions. Based on the surrogate WBGT value and the OEL at different metabolic rates, exposure decisions can be made from a table look-up. For this article, the selected metabolic rates were 115, 180, 300, and 450 W for rest, light, moderate, and heavy levels.[1] Because of the approximate nature of the surrogate metrics, these are called screening decisions in the current article.

The screening decisions were divided into four general categories. The four categories were: (1) less than the action or alert limit (<AL) for ACGIH and NIOSH, respectively; (2) less than the exposure limit (threshold limit value [TLV®] or REL); (3) hourly TWAs of work and recovery expressed in minutes (i.e., 15/45, 20/40, 25/35, 30/30, 35/25, 40/20, and 45/15); and (4) a Caution zone for an exposure greater than the exposure limit at rest.

Results

Heat Index Versus WBGT

Over the range of conditions described in the NOAA Heat Index chart with no radiant heat (Tg = Tdb), there was some dispersion of WBGT values at lower Heat Index values and more convergence at higher Heat Index values. Figure 1 illustrates the relationship between Heat Index [°F] and WBGT

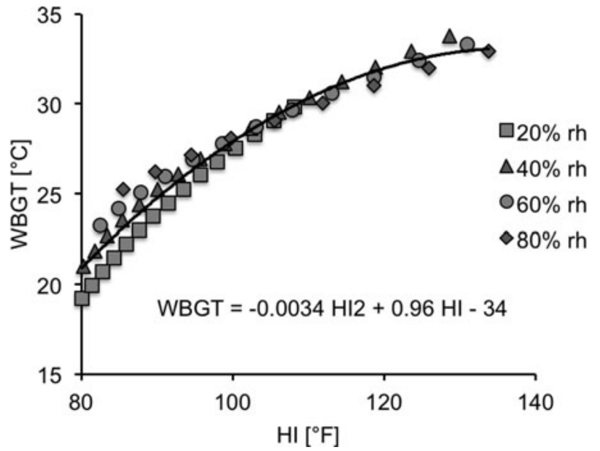

FIGURE 1. Relationship between Heat Index (HI) [°F] and WBGT [°C] for the combinations of air temperature and relative humidity report in charts by NOAA's National Weather Service.

[°C]. A second order power curve fit through all the data yielded,

$$\text{WBGT [°C]} = -0.0034\ \text{HI}^2 + 0.96\ \text{HI} - 34;\ \text{for HI [°F]} \quad \textbf{(12)}$$

Fitting a power function to all the data of the reverse relationship yielded,

$$\text{HI [°F]} = 0.24\ \text{WBGT}^2 - 9.3\ \text{WBGT} + 170;\ \text{for WBGT [°C]} \quad \textbf{(13)}$$

Adjusted Temperature Versus WBGT

Overall, the estimates of WBGT following the adjustments provided in NIOSH draft criteria document Table 6-2 were about 2°C-WBGT less than the reference values meaning that the estimates systematically underestimated the reference value. The underestimates were clearest at the two lower humidity levels. The estimated WBGTs also were clearly biased low with increasing radiant heat. Both of these findings suggested that the adjustments could be improved.

The simple optimization process described in the methods produced the adjustments provided in Table I. The mean overestimate of 0.1°C-WBGT was close to 0 and the standard deviation was reduced from 2.2 to 0.4°C-WBGT.

The relationship between Adjusted Temperature and WBGT at the reference conditions can be described by the following linear equation:

$$\text{WBGT [°C]} = 0.45\ \text{Tadj [°F]} - 16.7 \quad \textbf{(14)}$$

Figure 2 shows the relationship between Adjusted Temperature and WBGT for 18 combinations of relative humidity (6 levels) and radiant heat (3 levels). A line with some bias to overestimating WBGT by 0.7°C-WBGT (shown in Figure 2a and b) can be drawn by changing the intercept in the above equation. That is, the estimation equation proposed in this article is:

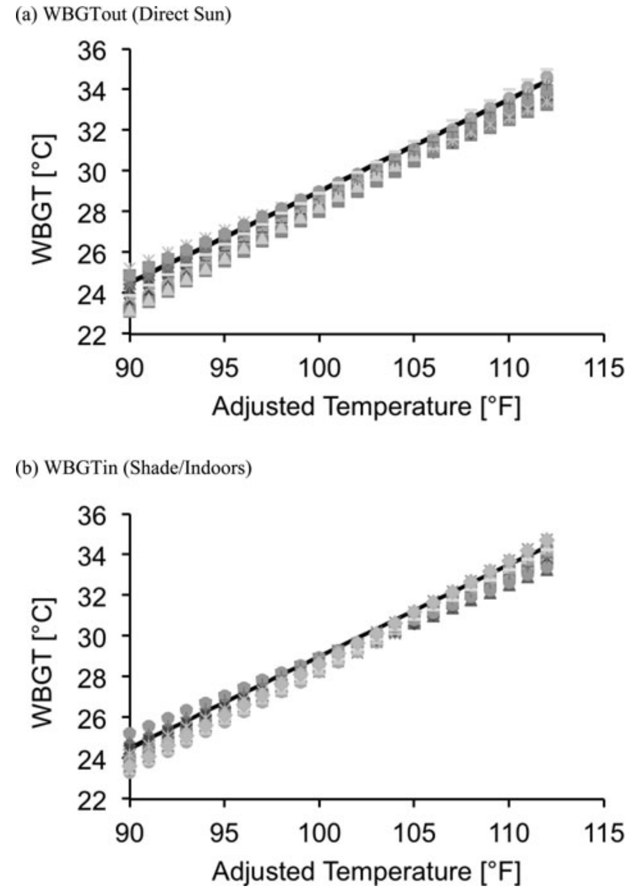

FIGURE 2. Relationship between Adjusted Temperature and (a) WBGTout (direct sun) and (b) WBGTin (shade or indoors). The estimation line is the same in both plots (WBGT = 0.45 Tadj – 16).

$$\text{WBGT [°C]} = 0.45\ \text{Tadj [°F]} - 16 \quad \textbf{(15)}$$

Screening Tables

Following the general format of exposure metric in the left column, next the estimated WBGT, and then columns for light, moderate, and heavy metabolic rate, the screening tables were constructed. Table II is for the Heat Index and WBGT in °F and Table III if for Adjusted Temperature and WBGT in °F. Tables IV and V are similar using °C for Heat Index, Adjusted Temperature, and WBGT.

DISCUSSION

The goal of this article is to explore the use of air temperature and relative humidity as a surrogate for WBGT, specifically, using Heat Index and Adjusted Temperature as methods to incorporate temperature and relative humidity. Because absolute humidity (water vapor pressure of the air)

TABLE II. Screening Table Based on Heat Index and Estimated WBGT in °F^A

Heat Index [°F]^A	Estimated WBGT [°F]	Light 180 W	Moderate 300 W	Heavy 415 W
85	73	<AL	<AL	<AL
86	74	<AL	<AL	<EL
87	75	<AL	<AL	<EL
88	75	<AL	<AL	<EL
89	76	<AL	<AL	<EL
90	77	<AL	<AL	<EL
91	77	<AL	<EL	<EL
92	78	<AL	<EL	<EL
93	79	<AL	<EL	<EL
94	79	<AL	<EL	<EL
95	80	<AL	<EL	<EL
96	80	<AL	<EL	45/15
97	81	<AL	<EL	45/15
98	81	<AL	<EL	45/15
99	82	<AL	<EL	40/20
100	82	<AL	<EL	35/25
101	83	<EL	45/15	35/25
102	83	<EL	45/15	30/30
103	84	<EL	45/15	30/30
104	84	<EL	40/20	25/35
105	85	<EL	40/20	25/35
106	85	<EL	35/25	20/40
107	86	<EL	30/30	20/40
108	86	<EL	30/30	15/45
109	86	<EL	25/35	15/45
110	87	<EL	20/40	15/45
111	87	<EL	20/40	Caution
112	88	45/15	15/45	Caution
113	88	45/15	15/45	Caution
114	88	40/20	15/45	Caution
115	89	35/25	Caution	Caution
116	89	30/30	Caution	Caution
117	89	25/35	Caution	Caution
118	89	25/35	Caution	Caution
119	90	20/40	Caution	Caution
120	90	15/45	Caution	Caution
121	90	Caution	Caution	Caution

[A]Work/Recovery cycles based on 115 W for resting metabolic rate and 60 min period; AL = Alert or Action Limit, EL = REL or TLV, and Caution = > EL at rest.
[B]Low Radiant Heat (Tg = Tdb + 7°F): Add 4°F to Heat Index; and High Radiant Heat (Tg = Tdb + 13°F): For WBGTout, add 6°F to Heat Index and for WBGTin (shade/indoors), add 9°F to Heat Index.

is the critical parameter in evaporative cooling, it is very important to remember that the air temperature and relative humidity must be concurrent measures.

For WBGT and the psychrometric relationships, SI units were used. The temperature units in this article for Heat Index (Table II) and Adjusted Temperature (Table III) were °F because that is the common use in the United States. We also provided tables in °C for Heat Index (Table IV) and Adjusted Temperature (Table V).

Fundamental to the analysis presented in this article was the estimation of natural wet bulb temperature. With air motion greater than 1 m/s and the absence of radiant heat, natural wet bulb temperature approaches the psychrometric wet bulb temperature, which is known directly from data available from the weather services. As the air speed approaches zero, the ability to estimate natural wet bulb temperature becomes uncertain.[17] Further, people are seldom still relative to the air and thus there is always some air motion around them.

TABLE III. Screening Table Based on Adjusted Temperature (see Table I for adjustments) and the Associated Estimated WBGT in °F[A]

Adjusted Temperature [°F]	Estimated WBGT [°F]	Light 180 W	Moderate 300 W	Heavy 415 W
90	74	<AL	<AL	<EL
91	75	<AL	<AL	<EL
92	76	<AL	<AL	<EL
93	77	<AL	<AL	<EL
94	78	<AL	<EL	<EL
95	78	<AL	<EL	<EL
96	79	<AL	<EL	<EL
97	80	<AL	<EL	45/15
98	81	<AL	<EL	45/15
99	82	<AL	<EL	45/15
100	82	<AL	<EL	35/25
101	83	<EL	45/15	30/30
102	84	<EL	45/15	25/35
103	85	<EL	40/20	25/35
104	86	<EL	30/30	20/40
105	86	<EL	25/35	15/45
106	87	<EL	20/40	Caution
107	88	45/15	15/45	Caution
108	89	35/25	Caution	Caution
109	90	20/40	Caution	Caution
110	90	Caution	Caution	Caution
111	91	Caution	Caution	Caution
112	92	Caution	Caution	Caution

[A]Work/Recovery cycles based on 115 W for resting metabolic rate and 60 min period; AL = Alert or Action Limit, EL = REL or TLV, and Caution = > EL at rest.

For these reasons a low air speed was chosen to represent a systematic bias toward high estimated WBGT and to avoid problems with still air. At high radiant heat levels, the radiant heat load on the natural wet bulb dominates the air speed effect.

Radiant heat effects were described as low (Tg = Tdb + 7°F) and high (Tg = Tdb + 13°F). The equivalent increases in °C were 3.9 and 7.2. These values were chosen from the original Adjusted Temperature method. For direct sunlight, the peak difference could be closer to 12°C (22°F).[15,22,23] The result would be an under-estimation of WBGT by 1.0°C-WBGT (i.e., Tg would be about 5°C more than modeled in the current article times the 0.2 weighting for Tg). This is within the variation due to other factors that relate the surrogates to WBGT.

Heat Index Versus WBGT

At low Heat Index values, the range of errors from the estimated WBGT values was about ±2°C-WBGT, and the error range converges to ±0.5°C-WBGT above a Heat Index of 100°F (see Figure 1). This means that there could be substantial errors in estimating WBGT with underestimates at higher relative humidities.

Steadman's rational model did not address radiant heat from the sun or any other source.[19] To be useful for outdoor conditions or locations with radiant heat sources, the Heat Index requires some adjustment. In considering an adjustment, it is first worthwhile to examine what effect radiant heat has on WBGT. If radiant heat effects are expressed as increases in globe temperature above the dry bulb temperature, then increases in WBGT are either 0.2 times the difference for direct sunlight conditions (WBGTout) or 0.3 times the difference for indoor or shaded conditions (WBGTin). As a rule of thumb, low radiant heat might be a difference of 4°C (7°F) and high of 7°C (13°F). Thus low radiant heat would increase the WBGT by about 1°C, and high radiant heat would increase it by 1.5 or 2°C for WBGTout or WBGTin, respectively. If Heat Index is used to estimate WBGT, then adding an adjustment to WBGT for radiant heat is straightforward (i.e., just adding the weighted increase in Tg above Tdb). Using the 12°C difference mentioned previously, the increase would be 3.5 and 2.5°C-WBGT for WBGTout or WBGTin, respectively.

If the interest is in changing the Heat Index directly to reflect the radiant heat, this becomes more complicated. For instance, it is not simply using the globe temperature as a substitute

TABLE IV. Screening Table Based on Heat Index and Estimated WBGT in °C [A]

Heat Index [°C] [B]	Estimated WBGT [°C]	Light 180 W	Moderate 300 W	Heavy 415 W
29.5	23.1	<AL	<AL	<AL
30.0	23.4	<AL	<AL	<EL
30.5	23.7	<AL	<AL	<EL
31.0	24.1	<AL	<AL	<EL
31.5	24.4	<AL	<AL	<EL
32.0	24.7	<AL	<AL	<EL
32.5	25.0	<AL	<AL	<EL
33.0	25.3	<AL	<EL	<EL
33.5	25.6	<AL	<EL	<EL
34.0	25.9	<AL	<EL	<EL
34.5	26.2	<AL	<EL	<EL
35.0	26.5	<AL	<EL	<EL
35.5	26.8	<AL	<EL	45/15
36.0	27.1	<AL	<EL	45/15
36.5	27.3	<AL	<EL	45/15
37.0	27.6	<AL	<EL	40/20
37.5	27.9	<AL	<EL	40/20
38.0	28.1	<AL	<EL	35/25
38.5	28.4	<EL	45/15	35/25
39.0	28.6	<EL	45/15	30/30
39.5	28.8	<EL	45/15	25/35
40.0	29.1	<EL	40/20	25/35
40.5	29.3	<EL	40/20	25/35
41.0	29.5	<EL	35/25	20/40
41.5	29.7	<EL	30/30	20/40
42.0	29.9	<EL	30/30	15/45
42.5	30.1	<EL	25/35	15/45
43.0	30.3	<EL	25/35	15/45
43.5	30.5	<EL	20/40	Caution
44.0	30.7	<EL	20/40	Caution
44.5	30.9	45/15	15/45	Caution
45.0	31.1	45/15	15/45	Caution
45.5	31.2	45/15	15/45	Caution
46.0	31.4	40/20	Caution	Caution
46.5	31.6	35/25	Caution	Caution
47.0	31.7	30/30	Caution	Caution
47.5	31.9	25/35	Caution	Caution
48.0	32.0	20/40	Caution	Caution
48.5	32.1	20/40	Caution	Caution
49.0	32.3	15/45	Caution	Caution
49.5	32.4	Caution	Caution	Caution

[A]Work/Recovery cycles based on 115 W for resting metabolic rate and 60 min period; AL = Alert or Action Limit, EL = REL or TLV, and Caution = > EL at rest.
[B]Low Radiant Heat (Tg = Tdb + 3.9°C): Add 2.2°C to Heat Index; and High Radiant Heat (Tg = Tdb + 7.2°C): For WBGTout, add 3.3°C to Heat Index and for WBGTin (shade/indoors), add 5°C to Heat Index.

for air temperature. This approach fails because the natural wet bulb temperature at a fixed relative humidity increases and that the increase influences the WBGT more than the increase of globe temperature above dry bulb temperature. The result of using globe temperature instead of air temperature to determine Heat Index is an overestimation of WBGT and thus the heat stress level. Because the relationship is a second order power function, the change in Heat Index to reflect the appropriate change in WBGT depends on the value of WBGT (or Heat Index). This can be seen in the first derivative of Heat

TABLE V. Screening Table Based on Adjusted Temperature (see Table I for adjustments) and the Associated Estimated WBGT in °C[A]

Adjusted Temperature [°C]	Reference WBGT [°C]	Light 180 W	Moderate 300 W	Heavy 415 W
32.0	23.4	<AL	<AL	<EL
32.5	23.8	<AL	<AL	<EL
33.0	24.2	<AL	<AL	<EL
33.5	24.6	<AL	<AL	<EL
34.0	25.0	<AL	<AL	<EL
34.5	25.4	<AL	<EL	<EL
35.0	25.8	<AL	<EL	<EL
35.5	26.2	<AL	<EL	<EL
36.0	26.6	<AL	<EL	<EL
36.5	27.0	<AL	<EL	45/15
37.0	27.4	<AL	<EL	45/15
37.5	27.8	<AL	<EL	40/20
38.0	28.2	<AL	<EL	35/25
38.5	28.6	<EL	45/15	30/30
39.0	29.0	<EL	45/15	25/35
39.5	29.4	<EL	35/25	20/40
40.0	29.8	<EL	30/30	20/40
40.5	30.2	<EL	25/35	15/45
41.0	30.6	<EL	20/40	Caution
41.5	30.9	45/15	15/45	Caution
42.0	31.3	40/20	Caution	Caution
42.5	31.7	30/30	Caution	Caution
43.0	32.1	20/40	Caution	Caution
43.5	32.5	Caution	Caution	Caution

[A]Work/Recovery cycles based on 115 W for resting metabolic rate and 60 min period; AL = Alert or Action Limit, EL = REL or TLV, and Caution = > EL at rest.

Index with respect to WBGT based on the power fit provided previously. Using delta notation,

$$\Delta \text{Heat Index}/\Delta \text{WBGT} = 0.48\ \text{WBGT} - 9.3 \qquad \textbf{(16)}$$

For the sake of discussion, a WBGT of 28°C represents a value of WBGT that is at the OEL for moderate work. Then the change is 4.1°F-HI/°C-WBGT. At the WBGT limit for light work, the relationship would be about 5.5°F-HI/°C-WBGT; and for heavy metabolic rate, about 3.4°F-HI/°C-WBGT. Choosing an intermediate exchange rate of 4°F-HI/°C-WBGT, an increase of 1°C-WBGT for moderate radiant heat could be equivalent to a change of 4°F of Heat Index. Similarly, high radiant heat could be a Heat Index increase of 6 or 9°F for WBGTout and WBGTin, respectively. These are the adjustments in Heat Index recommended in Tables II and IV.

Adjusted Temperature Versus WBGT

The initial analysis of the adjustments for radiant heat used the WBGTin formulation. It could be reasonably argued that the WBGTout condition was more appropriate. If WBGTout had been used, the systematic difference in WBGT for the high radiant heat condition would have been 0.7°C-WBGT lower. The resulting overall bias (about 1.6°C-WBGT) would have been somewhat lower but still much different than the reference condition and from the recommended adjustments contained in the draft NIOSH document.

A consequence of the approach taken to recommend adjustments for relative humidity and radiant heat was that for any combination of relative humidity and radiant heat adjustments, the relationship between Adjusted Temperature and WBGT was linear with a convergence of lines near an Adjusted Temperature of 103°F. There was some variation in slopes. These features can be seen in Figures 2a and 2b.

The recommended values for relative humidity adjustments were different from those proposed in the NIOSH draft criteria document for lower relative humidities. The relationship between relative humidity and adjustment was slightly nonlinear but linear interpolation is acceptable. See Figure 3 for which the relative humidity reference points are connected by straight lines. When a second order power function was fit to the values there was no discernible difference in the point-to-point lines and the power function, supporting the use of simple interpolation.

The notable departure was for the treatment of radiant heat. For the same reasons described for Heat Index, increasing the air temperature to the globe temperature value ignores

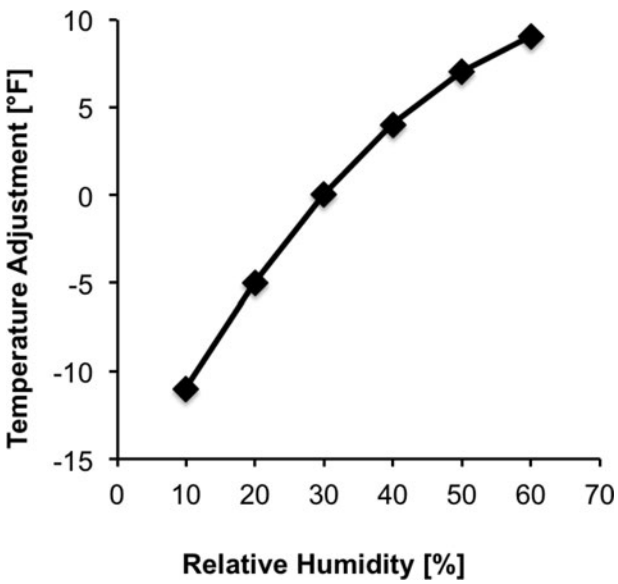

FIGURE 3. Relative humidity temperature adjustment [°F] for Adjusted Temperature determination.

the effects of humidity on evaporative cooling (i.e., it greatly exaggerates the loss of cooling capacity). That is why the recommended adjustments were substantially lower.

Screening Tables

In using surrogates like Heat Index and Adjusted Temperature to screen for heat stress exposure limits, the goal is to err toward false positive decisions. For Heat Index, the uncertainty between the estimated and actual WBGT was greatest below 100°F at lower humidities. Above a Heat Index of 100°F, the relationship was within 1°C-WBGT. For Adjusted Temperature, actual WBGT values were within a 2°C-WBGT range below the selected relationship over the entire range of Adjusted Temperature.

Tables II and III are presented in this article as screening tools for heat stress. Working from the NIOSH criteria documents[3,4] and the ACGIH TLV,[1] the tables provide the alternative index (i.e., Heat Index and Adjusted Temperature) using the relationships to estimate WBGT described in this article.

The metabolic rates were not specified in the NIOSH draft criteria document Table 6-2. Once the WBGT values associated with the Adjusted Temperature reference scenario were determined, combinations of values for metabolic rate at rest and the exposure decisions were explored to estimate the implicit metabolic rates for rest, light, moderate and heavy that would be consistent with the NIOSH REL. From this analysis, the metabolic rates were 90, 180, 300, and 430 W for rest, light, moderate, and heavy levels. The largest difference from the values of metabolic rate in Tables II and III was the resting rate of 115 W. While 115 W is high on a population basis, it is reasonable to believe that there will be some activity during the rest period and 115 W provides a margin of protection.

Use and Limitations

Approximations of WBGT

WBGT is a good index for heat stress assessments because it factors in important environmental contributors to heat stress assessment, which include air temperature, humidity, and speed plus radiant heat. Because it is an empirical index, WBGT and associated exposure assessment methods have inherent limits.[24,25] Surrogate measures of WBGT such as Heat Index and Adjusted Temperature are only approximations, which means that they should be used with care. It is for this reason that we recommend that Heat Index and Adjusted Temperature be used for screening rather than evaluation.

Tables II through V can be used in two ways. The first is to find the estimated WBGT from either Heat Index or Adjusted Temperature and then use that value to perform a heat stress assessment, remembering that the WBGT values are approximate. The second use follows the screening philosophy of the ACGIHTLV,[1] which is used only to determine if a more detailed analysis is appropriate.

Sampling Practice

Whether exposures occur outside or indoors, there can be considerable variation in WBGT values due to local conditions. The use of Heat Index and Adjusted Temperature may lead a user to treat environments as homogeneous. To understand the environmental contributors to heat stress, local and repeated measurements are necessary to characterize the exposure. Said another way, the limits of screening criteria as a gross approximation should be fully appreciated.

Concurrency of Measurement of Air Temperature and Relative Humidity

Heat Index and Adjusted Temperature employ relative humidity. Because the ability to cool by sweat evaporation is dictated by water vapor pressure (absolute humidity) and because relative humidity for a given water vapor pressure is very sensitive to dry bulb temperature, both dry bulb (air) temperature and relative humidity must be concurrent measures.

Estimation of Radiant Heat

Adjusted Temperature was based on two levels of radiant heat that were less than the peak radiant heat from the sun. These values were employed in this article. This poses two problems. Selecting the level of radiant heat is very subjective and more difficult without actual experience making globe temperature measurements. The actual WBGT may vary by 2°C-WBGT depending on the difference between actual and implicit values from the judgment.

While Heat Index assumes that there is no radiant heat, we have suggested a method to include its effects. This method depends on the same judgment as required by the Adjusted Temperature and a similar uncertainty for actual WBGT.

Air Movement

Neither Heat Index nor Adjusted Temperature includes air movement as a factor. Increasing air speed up to about 2 m/s will increase the rate of evaporative cooling. The analysis in this article sets air speed at 0.5 m/s. An air speed of 0.5 m/s represents a low value but not still air. If the air speed is less, then there will be a tendency for the estimated values of WBGT to move higher, which means there is a greater risk that WBGT will be underestimated. For higher air speeds, the actual WBGT will be less than the estimated value.

Level of Protection and Productivity

An OEL, by its nature, protects most workers. In the context of heat stress, the exposure limit is set so that most workers are expected to be able to maintain thermal equilibrium (compensable heat stress). Because there is a large inter-individual variation in heat stress tolerance, most workers can work above the OEL and still maintain thermal equilibrium. In this regard, the limit is protective. When a surrogate index (e.g., Heat Index or Adjusted Temperature) is used, any overestimation means that the level of heat stress is also overestimated. For this article, a bias toward overestimation was introduced in the Adjusted Temperature.

Small changes in WBGT can lead to large changes in the balance between work time and recovery time. So a bias toward overestimation of WBGT will lead to further losses in productivity if the screening data are used instead of following up with a detailed analysis.

CONCLUSION

Heat Index and Adjusted Temperature can be useful surrogates for WBGT to screen for potential heat stress exposures. As with any surrogate, there are approximations. Specifically, radiant heat level was a subjective judgment. Air motion was assumed to be low with attendant possibilities of overestimating WBGT at very low air speed and underestimating WBGT at higher air speeds.

The methods of estimating WBGT from either Heat Index or Adjusted Temperature can be used to estimate WBGT, which is then used in subsequent assessment, or to screen for heat stress levels using Tables II through V. Regardless of approach, the methods are for screening rather than a final determination. Good professional practice would use a detailed WBGT analysis following, for instance, the ACGIH TLV flow chart[1] or a rational model.[1,25,26]

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