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Can the USA National Weather Service Heat Index Substitute for Wet Bulb Globe Temperature for Heat Stress Exposure Assessment?

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Can the USA National Weather Service Heat Index Substitute for Wet Bulb Globe Temperature for Heat Stress Exposure Assessment?

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Masters of Science of Public Health
Department of Environmental and Occupational Health
with a concentration in Industrial Hygiene
College of Public Health
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Keywords: heat stress, National Weather Service, WBGT; Heat Index; occupational exposure limit

DEDICATION

“Our great weakness is giving up. The most certain way to succeed is always just to try just one more time.”

-Thomas Edison

I dedicate this thesis to my Mom and Dad, who continue to be amazing role models. Thank you for inspiring me and encouraging me to try my best in everything I do. I love you and couldn’t be more proud to have you as my parents.

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ABSTRACT

Heat stress occurs when the body cannot adequately cool itself due to the combined contributions of metabolic heat, environmental factors and clothing. Heat stress found in the workplace puts employees at risk of developing heat-related illnesses, disorders and could be fatal. The wet bulb globe temperature (WBGT) index is the current method used to assess environmental contributions to heat stress in an occupational setting. The purpose of this thesis was to explore whether the National Weather Service's Heat Index (HI) could substitute for the WBGT Index during occupational heat stress exposure assessment. The possibility of using the HI for heat stress exposure assessments was explored by first developing an occupational exposure limit based on the HI and then by comparing the HI to WBGT Index over a range of environments.

Data from 10 selected studies were reviewed and categorized into two groups (Classic Data and Progressive Data) based on the method used to determine the upper limit of the prescriptive zone. WBGT and HI values were estimated from the environmental data provided in the 10 studies and the metabolic demands were also noted. These data were used to illustrate the relationship between environment (WBGT and HI) and metabolic rate. Next the relationship between HI and WBGT was compared over a range of environments consisting of combinations of air temperature and percent relative humidity as defined by the NWS's Heat Index Chart. Finally the effects of adding a high radiant heat load ($T_g = T_{db} + 10$ °C) to the relationship between WBGT and HI was explored.

The HI occupational exposure limits were protective of the upper limit threshold points in a manner similar to WBGT. A greater spread in the Classic and Progressive upper limit data was observed above the occupational exposure limit when expressed as HI. High correlation was observed ($R^2 = 0.95$) between the WBGT Index and HI over a range of environments, assuming no radiant heat. The incremental increase in HI due to high radiant heat indicated a strong dependency on the absolute value of HI, which makes using HI to predict WBGT in radiant heat environments problematic.

Findings suggest the Heat Index could be used to assess heat stress exposures and to set occupational exposure limits for hot environments in the absence of high radiant heat.

CHAPTER 1: INTRODUCTION

The purpose of this study was to explore how the Heat Index (HI) might be used in heat stress assessments. A heat stress assessment generally considers the ability of the environment to support the loss of internally generated heat as well as the effects of clothing on a person's ability to exchange heat with the environment. Methods to assess occupational heat stress include at least the environment and metabolic rate. Occupational heat stress assessment methods vary by the data required and how the data are used to determine if an occupational exposure limit (OEL) is exceeded. This paper focuses on the Wet Bulb Globe Temperature (WBGT) Index method of heat stress assessment and works from the premise that the WBGT of the environment is a reference standard.

The current WBGT-based method for heat stress exposure assessment stems from the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limits (RELs) for occupational exposures to hot environments (NIOSH, 1986) and the ACGIH® Threshold Limit Values® (TLVs®) for heat stress (ACGIH, 2013). These limits are based on the efforts of Henschel and Dukes-Dobos. The basis for the REL and TLV exposure assessment strategy was to use the WBGT Index of Yaglou and Minard (1957) for an index of the environment and to use the studies of Lind and colleagues to establish the upper limit of the prescriptive zone.

The other focus of this paper is the Heat Index (HI) developed by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS). NOAA's NWS has popularized the HI by using it as a way of communicating heat stress risk to the public. The HI evolved from Steadman's efforts (Steadman, 1979a), who in 1979 developed a sultriness index similar in concept to the Wind Chill Index for cold. The research question of the current paper is whether the HI can be an alternative index of the environment compared to WBGT Index.

CHAPTER 2: LITERATURE REVIEW

Heat stress indices allow for the quantitative assessment of heat stress and are used to determine the limit where heat stress exposure would most likely lead workers to develop heat related illnesses. Two widely promoted heat stress indices are the WBGT Index and the NOAA NWS's Heat Index.

Environmental Indices

Macpherson (Macpherson, 1962) reviewed 19 indices that were either proposed or developed to assess heat stress between 1905 and 1960. He divided the indices into three classes based on what each index tried to assess. Class 1 indices measured the physical factors in the environment. Class 2 indices predicted human physiological strain produced by the environment. Class 3 indices were based on the heat exchange between the body and its environment.

Class 1 (Direct) indices, which measured the physical factors in the environment, included dry bulb temperature; wet-bulb temperature (Haldane, 1905); katathermometer (Hill, Griffith, & Flack, 1916); equivalent temperature (Dufton, 1929); and globe-thermometer temperature (Vernon, 1930 &1932). These indices measure or integrate the environmental factors (air temperature, air movement, and the effects humidity), but they do not assess the physiological effect directly.

Class 2 (Empirical) indices predicted human physiological strain produced by exposure to various factors (e.g. air temperature, humidity, air speed, radiant temperature, level of clothing and metabolic work rate). These indices include effective temperature (Houghten & Yaglou, 1923); corrected effective temperature (Bedford, 1946); equatorial comfort index (Webb,1959 & 1960); index of physiological effect (Robinson, Turrell, & Gerking, 1945) predicted four-hour sweat rate (McArdle, et al., 1947) thermal strain index (Lee, 1956 & 1958); and wet bulb globe temperature index (Yaglou and Minard, 1957). Typically, Class 2 indices represented combinations of environmental conditions that were subjectively equivalent.

Class 3 (Rational) indices included the thermal acceptance ratio (Ionides *et al*., 1943); operative temperature (Winslow, 1937); and heat stress index (Belding & Hatch, 1955 & 1956). Indices in Class 3 approximate the exchange of heat between a person and the environment.

Wet Bulb Globe Temperature Index

The WBGT Index was developed in the 1950's to control heat related illness in US military training camps. WBGT accounts for radiant radiation, air temperature, wind speed and air humidity that together make up the thermal environment under which can affect both human performance and human health. The WBGT value is calculated from a natural wet-bulb thermometer open to the ambient environment, a globe thermometer of 15 cm, and a dry-bulb that is protected from ambient radiation. Since its development, the WBGT has become the commonly used and widely accepted index for evaluating industrial heat stress (Bernard, 2002). In 1986, the National Institute for Occupational Safety and Health's (NIOSH) established six principal criteria for a standard heat stress index used in industrial settings. NIOSH's goal was to "establish safety criteria for workers who are exposed to severe thermal conditions" (Epstein & Moran, 2006). The 1986 NIOSH criteria for a heat stress evaluation included:

1) Be feasible and accurate at wide range of environmental and metabolic conditions.
2) Consider all important factors (such as environmental, metabolic, and clothing)

3) Measurements should reflect the worker's exposure, without interfering with his performance.
4) Exposure limits should be reflected by physiologic and/or psychological responses reflecting increased risk to safety or health.
5) Require measurements and calculations must be simple
6) The index must be applicable for setting limits under a wide range of environmental and metabolic conditions.

Based on these criteria, NIOSH recommended the WBGT Index be used as the standard heat stress index (Larranga, 2002). Since then, the WBGT Index has been used as the basis for assessing occupational heat stress.

WBGT Concept

Yaglou and Minard developed the WBGT Index to approximate the corrected effective temperature (CET), which similarly was developed to replace the effective temperature (ET) Index. Houghten and Yaglou's (1923) ET Index provided a method for determining the relative effects of air temperature and humidity on comfort (Epstein et al., 2006). However the ET Index lacked the ability to measure radiant heat. In 1932 Vernon and Warner proposed the CET Index by substituting the dry-bulb temperature with a black-globe temperature to allow radiation to be taken into account (Epstein et al., 2006). Yaglou and Minard later adjusted the CET Index by correcting the temperature of a 150 mm diameter black globe to account for the solar absorptivity of olive colored military clothing (Parsons, 2006). Yaglou and Minard approximated the CET Index by weighting the dry-bulb temperature (T_{db}), wet-bulb temperature (T_{nwb}) and black-globe temperature (T_g). Yaglou and Minard's modifications to the CET Index resulted in

WBGT Index's development. The WBGT Index assesses heat stress by responding to heat load from the environment as well as the cooling effects of evaporation (Budd, 2007). The WBGT Index is given by the equations:

$$\text{WBGTsolar load} = 0.7\text{Tnwb} + 0.2\text{Tg} + 0.1\text{Tdb} \tag{1}$$

Under indoor conditions (no solar load):

$$\text{WBGTno solar load} = 0.7\text{Tnwb} + 0.3\text{Tg} \tag{2}$$

Where Tnwb = natural wet-bulb temperature, Tg = globe temperature, and Tdb = dry-bulb temperature.

WBGT-Based Exposure Assessment

As noted by Lind (1970), "Minard et al. put forth a program of hot-weather hygiene and they set environmental limits for certain activities. These procedures eliminated heatstroke and markedly reduced the number of milder heat disorders. Clearly, thermal limits, when carefully applied, can successfully reduce heat disorders." This observation characterized the general recognition that there could be occupational exposure limits for heat stress.

The process started with a paper by Lind that demonstrated how within a certain range of environmental conditions, the body's core temperature is driven only by the metabolic demand. This range was known as the prescriptive zone (Lind, 1963a, Kuhlemeier et al., 1977). Above the prescriptive zone the body's core temperature was driven by environmental conditions. The transition between the metabolically-driven core temperature and the environmentally-driven core temperature was called the Upper Limit Prescriptive Zone (Lind, 1963a). Three other papers by Lind and colleagues demonstrated the validity of the Upper Limit Prescriptive Zone. NIOSH published a revised recommended criteria for a heat stress standard, which based the Recommended Exposure Limit (REL) on this work.

While OSHA never promulgated a heat stress standard, other organizations such as the ACGIH adopted an occupational heat stress exposure limit similar to the NIOSH REL.

Heat Index

In 1980, the Heat Index was adopted by the National Oceanic Atmospheric Administration’s (NOAA) National Weather Service (NWS). The Heat Index is widely used in public service advisories. The NWS uses the Heat Index values and information about the local climate to decide whether or not an excessive heat-related concern (such as outlooks, watches and warnings/advisories) is necessary.

Heat Index Concept

The Heat Index was originally developed by Steadman as an assessment for sultriness, but commonly referred to as the Apparent Temperature. Parameters involved in Apparent Temperature were water vapor pressure, surface area of skin, significant diameter of a human, clothing, core temperature, activity, effective wind speed, clothing resistance to heat transfer, radiation to and from the skin’s surface, sweating rate, ventilation rate, skin resistance to heat transfer, and surface resistance to moisture transfer (Rothfusz, 1990). Steadman’s Apparent Temperature assessed thermal comfort by using an iterative solution for multiple variables in multiple equations that represent the body’s heat and moisture transfer. This calculation was completed for combinations of air temperature and humidity and the resulting values were reported in two tables. These tables were based on air temperature and the type of moisture used, either relative humidity or dew point temperature (Anderson, Bell & Peng, 2013) (Steadman, 1979a).

Steadman's tabulated data was later approximated by Rothfusz (using a multiple regression analysis) into a single approximate Heat Index equation using air temperature and relative humidity. The derived Heat Index regression equation is:

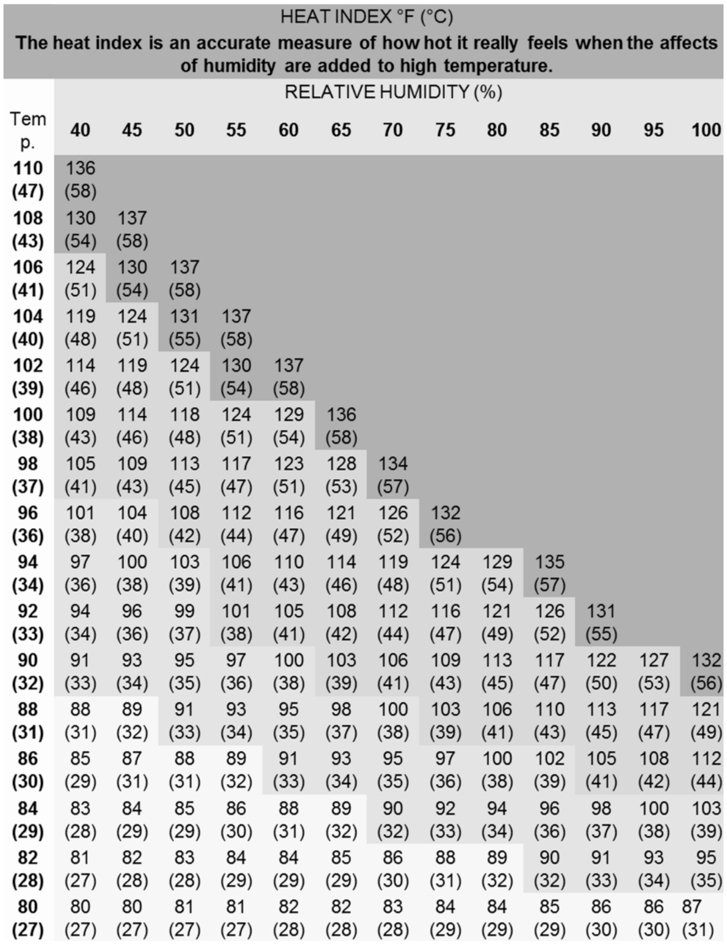
$$\mathrm{HI} = -42.379 + 2.04901523T + 10.14333127R - 0.22475541TR - 6.83783\mathrm{x}10^{-3}T^2 - 5.481717x\ 10^{-2}R^2 - 1.99x10^{-6}T^2R^2 \quad (3)$$

Where T = ambient dry bulb temperature (°F); R = relative humidity (%); and the degree of error = ±1.3°F.

The NOAA's Heat Index chart is another way to find the Heat Index. Given specific air temperature and relative humidity values, one can use the Heat Index chart to visually determine the Heat Index temperature.

Heat Index Exposure Assessment

The Heat Index chart is used to relate temperature values to likelihood of developing heat-related illnesses. For example HI values >130°F are categorized as Extreme Danger and are associated with a health threat of heat stroke (NOAA, 2014). The rationale for these levels was not found during review of the literature.

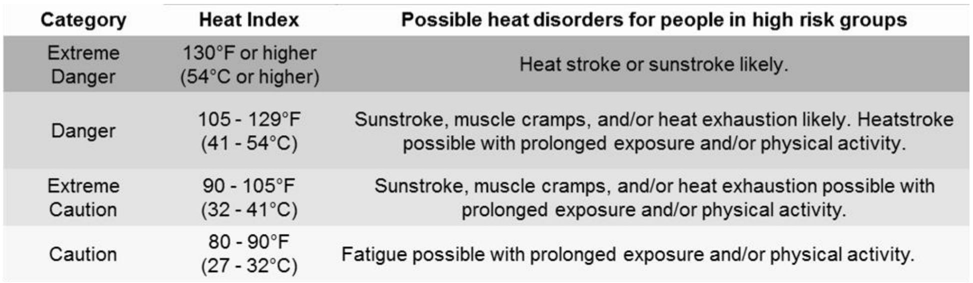


HEAT INDEX °F (°C)

The heat index is an accurate measure of how hot it really feels when the affects of humidity are added to high temperature.

	RELATIVE HUMIDITY (%)												
Temp.	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
110 (47)	136 (58)												
108 (43)	130 (54)	137 (58)											
106 (41)	124 (51)	130 (54)	137 (58)										
104 (40)	119 (48)	124 (51)	131 (55)	137 (58)									
102 (39)	114 (46)	119 (48)	124 (51)	130 (54)	137 (58)								
100 (38)	109 (43)	114 (46)	118 (48)	124 (51)	129 (54)	136 (58)							
98 (37)	105 (41)	109 (43)	113 (45)	117 (47)	123 (51)	128 (53)	134 (57)						
96 (36)	101 (38)	104 (40)	108 (42)	112 (44)	116 (47)	121 (49)	126 (52)	132 (56)					
94 (34)	97 (36)	100 (38)	103 (39)	106 (41)	110 (43)	114 (46)	119 (48)	124 (51)	129 (54)	135 (57)			
92 (33)	94 (34)	96 (36)	99 (37)	101 (38)	105 (41)	108 (42)	112 (44)	116 (47)	121 (49)	126 (52)	131 (55)		
90 (32)	91 (33)	93 (34)	95 (35)	97 (36)	100 (38)	103 (39)	106 (41)	109 (43)	113 (45)	117 (47)	122 (50)	127 (53)	132 (56)
88 (31)	88 (31)	89 (32)	91 (33)	93 (34)	95 (35)	98 (37)	100 (38)	103 (39)	106 (41)	110 (43)	113 (45)	117 (47)	121 (49)
86 (30)	85 (29)	87 (31)	88 (31)	89 (32)	91 (33)	93 (34)	95 (35)	97 (36)	100 (38)	102 (39)	105 (41)	108 (42)	112 (44)
84 (29)	83 (28)	84 (29)	85 (29)	86 (30)	88 (31)	89 (32)	90 (32)	92 (33)	94 (34)	96 (36)	98 (37)	100 (38)	103 (39)
82 (28)	81 (27)	82 (28)	83 (28)	84 (29)	84 (29)	85 (29)	86 (30)	88 (31)	89 (32)	90 (32)	91 (33)	93 (34)	95 (35)
80 (27)	80 (27)	80 (27)	81 (27)	81 (27)	82 (28)	82 (28)	83 (28)	84 (29)	84 (29)	85 (29)	86 (30)	86 (30)	87 (31)

Figure 2.1: Heat Index Chart (NOAA, 2009).



Category	Heat Index	Possible heat disorders for people in high risk groups
Extreme Danger	130°F or higher (54°C or higher)	Heat stroke or sunstroke likely.
Danger	105 - 129°F (41 - 54°C)	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heatstroke possible with prolonged exposure and/or physical activity.
Extreme Caution	90 - 105°F (32 - 41°C)	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity.
Caution	80 - 90°F (27 - 32°C)	Fatigue possible with prolonged exposure and/or physical activity.

Figure 2.2: Health Risks linked to various Heat Index categories (NOAA, 2009).

CHAPTER 3: METHODS

Multiple steps were taken to explore how the HI might be used in heat stress assessments. The first step to accomplish this was to use HI instead of WBGT to set an occupational exposure limit following the method used by NIOSH to set the REL. Then the HI was compared to WBGT over a range of possible environments.

Psychrometric Relationships

To make these comparisons, data provided in the papers were used to estimate the WBGT and the HI. The following relationships were used as appropriate based on a set of Excel user defined functions made available by Bernard (see http://personal.health.usf.edu/tbernard/HollowHills/Psychro_UDF_Pkg_v10.zip).

When air temperature (Tdb) and psychrometric wet bulb temperature (Tpwb) were reported, then vapor pressure (Pa) was calculated as:

$$Pa = 0.6105 * \mathrm{Exp}(17.27 * Tpwb / (Tpwb + 237.3)) - 0.067 * (Tdb - Tpwb) \qquad (4)$$

When Tdb and Pa were reported, then Tpwb was solved iteratively such that the above equation is solved. Natural wet bulb temperature (Tnwb) was estimated as:

$$Tpwb + 1\ ^{\circ}C \qquad (5)$$

The saturation water vapor pressure (Psat) at the given Tdb was:

$$Psat = 0.6105 * \mathrm{Exp}(17.27 * Tdb / (Tdb + 237.3)) \qquad (6)$$

Then percent relative humidity (%rh or R) was determined from the water vapor pressures as:

$$\%rh = 100 * Pa / Psat \quad (7)$$

The Heat Index was estimated from the Tdb and %rh using the Rothfusz equation described above.

Setting an Occupational Exposure Limit using Heat Index

The WBGT-based exposure assessment was based on four studies by Lind. Since that time there are other studies that have sought to articulate the upper sustainable heat stress limit.

Data

Data from ten studies were categorized into groups labeled the Classic Data and Progressive Data. The two groups of data were then used to explore the relationship between the environmental index and metabolic rate. These are summarized in Tables 1 and 2. For each study, the tables provide the average metabolic rate of the participants. The WBGT and HI were based on the average environmental conditions at the upper limit.

Referring to Table 1, the first four studies were those of Lind and colleagues that were used to establish the occupational exposure limit. In assessing Lind's original data, it is worth noting that the participants were unacclimatized and semi-nude. The NIOSH investigators noted from other studies comparing unacclimatized to acclimatized and comparing semi-nude to work clothes that the effects from both comparisons were approximately equal in magnitude and opposite in direction. Thus, the data could be used directly, without adjustments. The fifth study (Kuhlemeier, et al., 1977) used Lind's protocol for assessing the ULPZ for men wearing work clothes during hot and cold seasons and for hot and cold working conditions. The data reported in the table are for the hot workers in the hot season, who were assumed to be acclimatized.

Table 1. Studies using Lind's protocol to find an upper limit to the prescriptive zone (Lind 1963a) and to validate the limit.

Study	Number of Participants	Metabolic Rate [W]	WBGT [°C]	HI [°C]
Lind 1963a	2	210	30.0	42
Lind 1963a	3	350	27.6	36
Lind 1963a	2	490	26.6	34
Lind 1970 et al	2	350	29.7	41
Lind 1963b	2	350	29.6	41
Lind 1970	25	350	28.9	39
Kuhlemeier et al., 1977	~20*	270	25.7†	32†
Kuhlemeier et al., 1977	~20*	354	28.4	38
Kuhlemeier et al., 1977	~20*	490	26.2	33

* The papers reporting the data were not specific about how many were in the hot jobs category. There were 46 participants altogether, so the 20 represents about half.

† The WBGT and HI are not consistent with other data and appear to be too low.

Belding and Kamon developed a progressive heat stress protocol that was intended to be a faster way to determine the upper limit of sustainable heat stress by determining when a person lost the ability to thermal regulate (Belding & Kamon, Evaporative coefficients for prediction of safe limits in prolonged exposures to work under hot conditions., 1973). This protocol was further adapted by Kenney (Kenney, Mikita, Havenith, Puhl, & Crosby, 1993) and Bernard (Bernard, Luecke, Schwartz, Kirkland, & Ashley, 2005, Bernard, Caravello, McCullough, & Ashley, 2008b). Their results for acclimatized participants wearing work clothes are reported in Table 2.

Table 2. Studies using the progressive heat stress protocol to find an upper exposure limit.

Study	Number of Participants	Metabolic Rate [W]	WBGT [°C]	HI [°C]
Belding & Kamon 1973	14	220	31.9	48
Belding & Kamon 1973	14	220	33.9	57
Belding & Kamon 1973	14	220	34.5	
Belding & Kamon 1973	14	280	33.4	54
Belding & Kamon 1973	14	280	33.1	53
Belding & Kamon 1973	14	360	29.9	42
Belding & Kamon 1973	14	360	31.5	47
Belding & Kamon 1973	14	360	33.4	54
Belding & Kamon 1973	14	360	34.2	
Belding & Kamon 1973	14	220	34.2	
Belding & Kamon 1973	14	220	35.3	
Belding & Kamon 1973	14	220	35.3	
Belding & Kamon 1973	14	280	34.2	
Belding & Kamon 1973	14	280	34.5	
Belding & Kamon 1973	14	360	34.2	
Belding & Kamon 1973	14	360	33.1	53
Belding & Kamon 1973	14	360	34.8	
Belding & Kamon 1973	14	360	34.8	
Kamon et al., 1978	8	305	33.1	54
Kamon et al., 1978	8	305	33.5	54
Kamon et al., 1978	8	305	33.9	55
Kamon et al., 1978	8	305	33.7	52
Kamon et al., 1978	8	305	33.5	
Kamon et al., 1978	8	305	33.8	
Kamon et al., 1978	8	305	34.5	
Kenney et al., 1993	6	400	28.7	41
Kenney et al., 1993	6	400	29.6	41
Bernard et al., 2005	14	300	36.6	
Bernard et al., 2005	14	300	36.5	
Bernard et al., 2005	14	300	36.0	
Bernard et al., 2008b	29	360	47.6	57

Occupational Exposure Limit Determination for Heat Index

An occupational exposure limit for the WBGT is described by ACGIH's TLV equation TLV[°C – WBGT] = 56.7 – 11.5 log10 M[W]. The WBGT and HI data from the ten studies in Tables 1 and 2 were used to posit a relationship between WBGT and HI. The result was the following equation:

$$HI = 0.18\ WBGT^2 - 8.0\ WBGT + 116 \qquad (8)$$

$(R^2 = 0.98)$

Prediction of WBGT from HI

To examine how well WBGT could be predicted from HI values, combinations of air temperature and relative humidity from Figure 2.1 along with psychrometric relationships described above (see equations 4 – 7) were used to estimate WBGT for the same combinations. It was assumed that there was no radiant heat; that is, dry bulb and globe temperatures were considered to be the same (Tdb = Tg).

CHAPTER 4: RESULTS

Occupational Exposure Limit

The first step in the analysis of Heat Index as an environmental index is to examine the outcome if HI had been used instead of WBGT. For reference, Figure 4.1 is the relationship between the upper limit expressed as WBGT at the range of metabolic rates from Tables 1 and 2. Figure 4.1 is analogous to Figure 4.2 except that HI was used instead of WBGT.

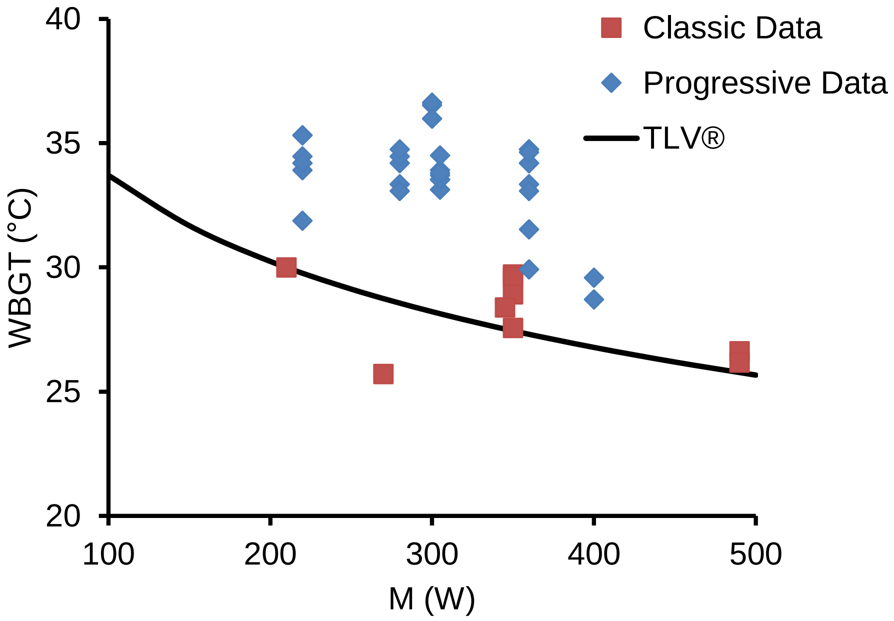


Figure 4.1: Occupational Exposure Limit Based on WBGT.

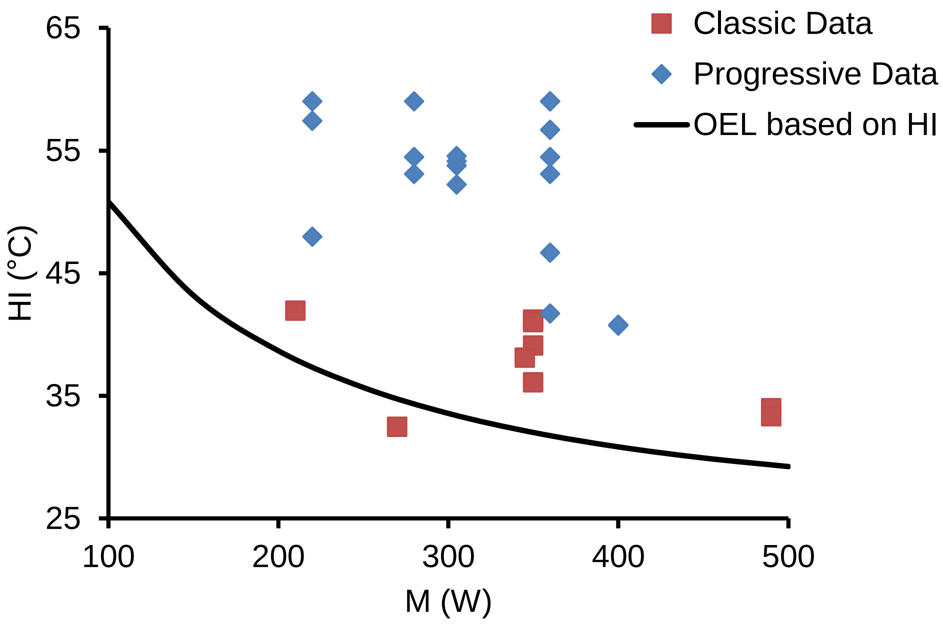


Figure 4.2: Occupational Exposure Limit Based on Corresponding HI.

Exploring the WBGT versus HI

To examine the relationship between WBGT and HI, the WBGT was computed for all combinations of air temperatures (Tdb ° C) and percent relative humidity (%rh) in whole numbers within the range of data used by NOAA in Figure 2.1. Assuming no radiant heat (Tg = Tdb), the relationship between the two indices is shown in Figure 4.3.

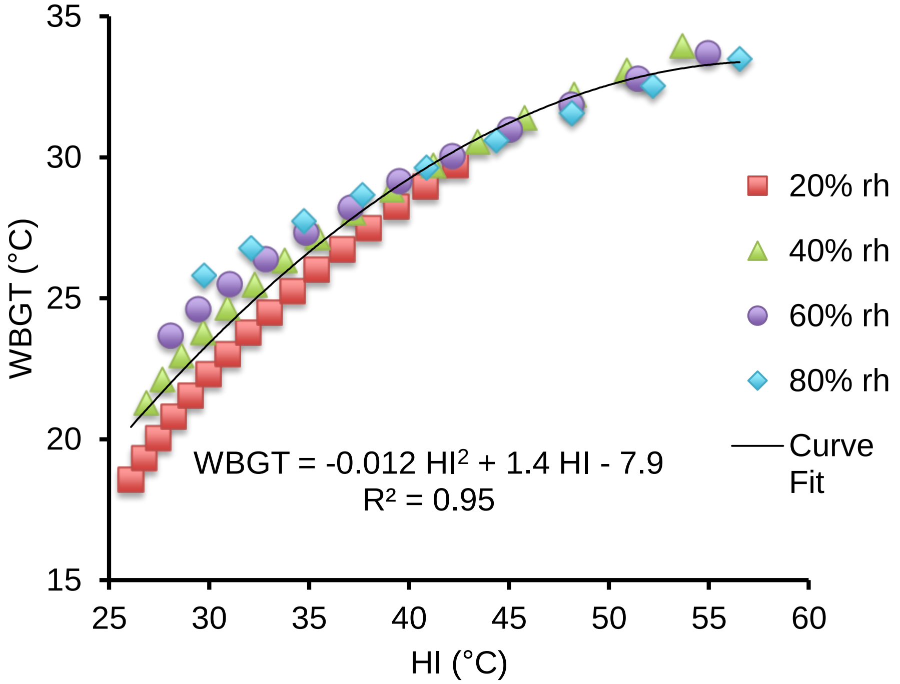


Figure 4.3: Comparison of WBGT and HI over the Range of Dry Bulb Temperatures and Relative Humidities in Figure 2.1.

CHAPTER 5: DISCUSSON

Occupational Exposure Limit Determinations

The OEL based on WBGT Index is shown in Figure 4.1. Lind's data (Lind, 1963a) plus that of Kuhlemeier et al (Kuhlemeier, Miller, Dukes-Dobos, & Jensen, 1977) as summarized in Table 1, were plotted as the Classic data. While Kuhlemeier followed Lind's original protocol for the Upper Limit of the Prescriptive Zone, the point at 280 W and 26 °C-WBGT was clearly lower than the other data. This outlying point was inconsistent within Kuhlemeier's own study (e.g. the point at 500 W matches Lind's data). Because point 280 W and 26 °C-WBGT is not biologically plausible, it is safe to ignore.

The data from progressive heat stress protocols (see Table 2) are also illustrated in Figure 4.1. Unpublished data from USF suggested that the progressive heat stress protocol results were biased high by a couple of °C-WBGT and this appeared to be the case in Figure 4.1. That is, the progressive data were above the OEL.

The relationship between WBGT and HI based on the 10 studies of Tables 1 and 2 was used to transform the WBGT-based OEL into HI as seen in Figure 4.2. Again the Classic and Progressive data were included in Figure 4.2 with the HI determined from the reported experimental data (see Tables 1 & 2). The Classic and Progressive data followed a very similar overall pattern, with greater spread of the data above the OEL. Figure 3 supported the idea that the HI may substitute for WBGT.

The spread seen in Figure 4.2 was expected because small changes in WBGT were associated with large changes in HI when the WBGT is greater than 30 °C-WBGT or equivalently when the HI is greater than 40 °C.

Prediction of WBGT from HI

Figure 4.3 shows the relationship between WBGT and HI over the range of conditions described in Figure 2.1 for the HI. Figure 4.3 is true for conditions that do not have radiant heat sources. The overall quality of the relationship is seen in a high coefficient of determination ($R^2 = 0.95$). It is also worth noting that the deviations of the individual data from the best fit curve decrease with increasing HI such that approaching and exceeding the OEL, the data are much closer than at lower values. This points to some utility in estimating WBGT from HI in the absence of radiant heat.

Under a usually high radiant where $T_g = T_{db} + 10$ °C, there would be no change in HI but the $WBGT_{in}$ would be 3 °C-WBGT higher and $WBGT_{out}$ would be 2 °C-WBGT higher. In general, the $WBGT_{in}$ is higher by $0.3\ (T_g - T_{db})$, and the $WBGT_{out}$ is higher by $0.2\ (T_g - T_{db})$. So, in a very straightforward way, WBGT can be estimated by the following:

$$WBGT_{in} = -0.012\ HI^2 + 1.4\ HI - 7.9 + 0.3\ (T_g - T_{db}) \qquad (9)$$

$$WBGT_{out} = -0.012\ HI^2 + 1.4\ HI - 7.9 + 0.2\ (T_g - T_{db}) \qquad (10)$$

Another approach might be to suggest an increase in the ambient HI that accounts for an increase in radiant heat. That is, determine the HI first and then apply a correction. Following the example of an increase in globe temperature of 10 °C, the adjustment depends on whether indoor or outdoor (direct sun light) conditions apply. Figure 4.4 illustrates the fact that the increase in HI depends on the starting value for HI and on whether indoor out outdoor conditions apply.

Overall, the HI’s ability to predict the WBGT when accounting for radiant heat conditions is suspect.

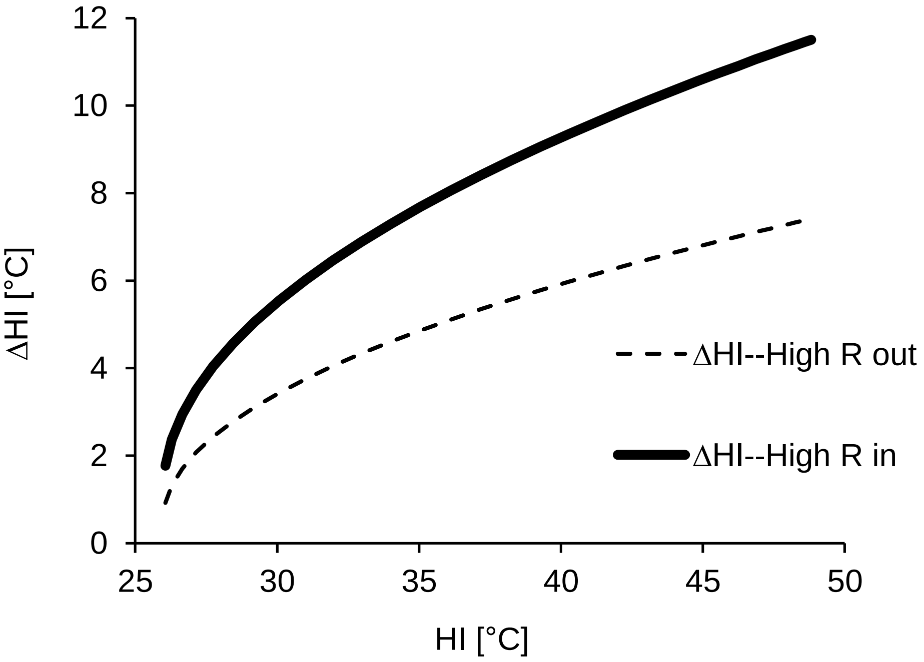


Figure 4.4: Change in HI associated with a change in WBGT due to high radiant heat (Tg = Tdb + 10 °C).

There could be a temptation to add a fixed value to air temperature prior to computing an HI that would account for radiant heat. Some care must be taken with this approach because increasing the air temperature to determine HI may have a large effect on the humidity (water vapor pressure) that would result in a larger increase in HI and thus resulting in a disproportionately high estimate of the heat stress level.

CHAPTER 6: CONCLUSIONS

Findings suggest exposure limits expressed as the WBGT or expressed as the HI are both protective of human health. Indicating that the HI could substitute for the WBGT when establishing occupational exposure limits for hot environments. When radiant heat is absent, there is a high correlation between WBGT and HI ($R^2 = 0.95$). Accounting for radiant heat affects HI ability to effectively estimate the WBGT. When radiant heat is present, HI is only useful to the extent that it is used to predict a WBGT and then the WBGT is adjusted for radiant heat. It appears, however, that HI could be used as a substitute for WBGT during heat stress exposure assessments.

REFERENCES

ACGIH, American Conference of Governmental Industrial Hygienists. (2013). *2013 Threshold Limit Values & Biological Exposure Limits.* Signature Publications.

Anderson, G. B., Bell, M. L., & Peng, R. (2013). Metjods to Calculate the Heat Index as an Exposure Metric in Environmental Health Research. *Environmental Health Perspectives*, 121(10): 1111- 1119.

Belding, H. S., & Hatch, T. F. (1955). Index of Evaluating heat stress in terms of resulting physiological strains. *Heating Piping Air Conditioning*, 27: 129-136.

Belding, H. S., & Hatch, T. F. (1956). Index of Evaluating heat stress in terms of resulting physiological strains. *ASHRAE Trans.*, 62: 213 - 228.

Belding, H. S., & Kamon, E. (1973). Evaporative coefficients for prediction of safe limits in prolonged exposures to work under hot conditions. *In Federal Proceedings*, Vol. 32, No. 5, 1598-1601.

Bernard, T. E., Caravello, V., McCullough, E. A., & Ashley, C. D. (2008). Apparent Evaporative Resistance at Critical conditions for five clothing ensembles. *Journal of Occupational and Envirornmental Hygiene*, 1-5.

Bernard, T. E., Luecke, C. L., Schwartz, S. K., Kirkland, K. S., & Ashley, C. D. (2005). WBGT Clothing Adjustments for Four Clothing Ensembles Under Three Relative Humidity Levels. *Journal of Occupational and Enviromental Hygiene*, 251-256.

Budd, G. (2007). Wet-bulb globe temperature (WBGT) - its history and its limitations. *Journal of Science and Medicine in Sport*, 20-32.

Dufton, A. F. (1929). The eupatheostat. *Journal of Science Instruments*, 6: 249 - 251.

Dukes-Dobos, F. N., & Henschel, A. (1973). Development of permissible heat exposure limits for occupational work. *ASHRAE Journal*, 15: 57-62.

Epstein, Y., & Moran, D. (2006). Thermal omfort and the heat stress indicies. *Industrial Health*, 388 - 398.

Gagge, A. (1941). In temperature. Its measurement and control in science and industry. *American Journal of Physiology*, 544.

Haldane, J. S. (1905). Influence of High Temperatures. *Journal of Hygiene*, 5: 494 - 513.

Hill, L. W., Griffith, O., & Flack, M. (1916). The measurement of the rate of heat loss at body temperature by convection, radiation and evaporation. *Philos. Trans Royal Society*, 207B: 183 - 220.

Ionides, M., Plumme, J., & Siple, P. (1945). *Report from climatology and environmental protection section.* U.S.: Office of the quatemaster general .

Kamon, E., Avellini, B., & Krajewski, J. (1978). Physiological and biophysical limits to work in the heat for clothed men and women. *Journal of Applied Physiology: Respiratory, Environmenal and Excercise Physiology*, 44(6) : 918 - 925.

Kenney, W. L., Mikita, D. J., Havenith, G., Puhl, S. M., & Crosby, P. (1993). Simultaneous derivation of clothing-specific heat exchange coefficients. *Medical Science of Sports Excercise*, 25(2): 283-289.

Kuhlemeier, K. V., Miller, J. M., Dukes-Dobos, F., & Jensen, R. (1977). Determinants of the Upper Limit the Prescriptive Zone of Industrial Workers. *Journal Applied Physiology*, 43:347-348.

Larranga, M. (2011). Thermal Standards and Measurement Techniques. In D. Anna, *The Occupational Environment: Its Evaluation, Control, and Managment* (pp. 918-951). Fairfax: American Industrial Hygiene Association.

Lee, D. H. (1955). Paper to the Twentieth International Physiological Congress. *Brussels*.

Lee, D. H. (1958). Proprioclimates of man and domestic animals. *Arid zone research-X Climatology, Reviews of Research*, 102 - 125.

Lind, A. R. (1963a). A physiology criterion for setting thermal environmental limits for everyday work. *Journal of Applied Physiology*, 18(1): 51-56.

Lind, A. R. (1963b). Physiological effects of continuous intermittent work in heat. *Journal of Applied Physiology*, 18(1): 57-60.

Lind, A. R. (1970). Effect of indiviual variation on upper limit of prescriptive zone of climates. *Journal of Applied Physiology*, 28(1): 57- 62.

Lind, A. R., Humphreys, K. J., Collins, K. F., & Sweetland, K. F. (1970). Influence of age ans daily duration of exposure on responses of men to work in heat. *Journal of Applied Physiology*, 28(1): 50-56.

Macpherson, R. K. (1962). The assesment of the thermal environments. A review. *British Journal of Industrial Medicine*, 151-164.

McArdle, B., Dunham, W., Holling, H., Ladel, W., Scott, J. W., Thomson, M. L., & Weiner, J. S. (1947). The prediction of the physiological effects of warm and hot environments. *Med Res Council, London RNP Report 47/391*.

McDonald, O. (2008). Heat Stress: Improving safety in the Arabian Gulf Oil and Gas Industry. *Professional Safety-Journal of the American Society of Safety Engineers*, 31-36.

Moran D, e. a. (2001). An environmental stress index (ESI) as substitue for the wet bulb globe temperature (WBGT). *Journal of Thermal Biology*, 427-431.

Moran, D., Shitzer, A., & Pandolf, K. (1998). A physiological strain index to evaluate heat stress. *American Journal Physiology*, 129 - 134.

NIOSH. (1986). *Criteria for a recommended standard: occupational exposures to hot environment.* Washington DC.: DHHS (NIOSH) Occupational Safety and Health.

NOAA. (2009). *Heat Index Chart.* NOAA National Weather Service: Peachtree, GA Office, http://srh.noaa.gov/ffc/?n=hichart. Retrieved from Heat Index: http://srh.noaa.gov/ffc/?n=hichar.

NOAA. (2013). National Weather Service Heat Index. *Heat Index.* National Oceanic and Atmospheric Administration, http://www.wrh.noaa.gov/psr/general/safety/heat/heatindex.png.

NOAA. (2013). National Weather Service Heat Index. *Heat Index.* National Oceanic Atmospheric Association, http://www.nws.noaa.gov/os/heat/images/heatindex.png.

NOAA. (2014). *Heat: A Major Killer*. Retrieved from NOAA's National Weather Service: Office of Climate, Water, and Weather Services: http://www.nws.noaa.gov/os/heat/index.shtml#heatindex

Parsons, K. (2003). *Human Thermal Environments: The effects of hot, moderate, and cold environments on human health, comfort and performance* (2nd ed.). New York: Taylor & Francis Inc.

Robinson, S., Turrell, E. S., & Gerking, S. D. (1945). Physiologically equivalent conditions of air temperature and humidity. . *American Journal Physiol.*, 143: 21 - 32.

Steadman, R. (1979a). The assessment of sultriness.part I: a temperature-humidity index Based of human physiology and clothing science. *American Meterological Society*, 861-874.

Vernon, H. M. (1930). The influence of humidity of the air on capacity of work at high temperatures. *Journal of Physiol. Lond.*, 70.

Vernon, H. M., & Warner, C. G. (1932). The influence of humidity of the air on capacity of work at high temperatures. *Journal of Hygiene, Camb.*, 32: 431.

Webb, C. G. (1959). An analysis of some observations of thermal comfort in an equatorial climate. *British Journal Ind. Med.*, (16) 3: 297-310.

Winslow, C., Herrington, E., & Gagge, A. (1937). Physiological resactions of the human body o varying environmental temperatures. *American Journal of Physiology*, 1 - 22.

Yaglou, C., & Minard, D. (1957). Control of heat casualties at military training centers . *American Medical Association Archive of Industrial Health*, 302 - 316.

Zanobetti, A., O'Neill, M. S., Gronlund, C. J., & Schwartz, J. D. (2012). Summer temperature variability and long-term survival among elderly people with chronic disease. *Proceedings of the Natural Academy of Sciences*, 109(17): 6608 - 6613.