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Physiological Evaluation of the WBGT Index for Occupational Heat Stress

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In order to examine whether identical WBGT levels achieved by different combinations of environmental thermal parameters result in equivalent physiological responses, three fit young men were exposed for 2 hours at WBGT levels of 85°F and 89°F, each under four different combinations of natural wet bulb, globe temperature, and air speed. Air temperature and metabolic work were kept constant, at 96°F and 289 kcal/hr, respectively. Heart rate, rectal temperature, forehead skin temperature, and sweat loss of the subjects were determined during the steady-state phase of the exposures. It was found that condition in which the ambient humidity was relatively higher resulted in higher heart rate, body core temperature, forehead temperature, and sweat loss. Under dry conditions, the strain of exposure at WBGT 85 and 89 could not be differentiated. Under these conditions computed HSI values and observed Botsford wet globe readings were better indicators of relative strain resulting from the exposures than WBGT.

THE U. S. NATIONAL INSTITUTE of Occupational Safety and Health (NIOSH) has proposed that a wet-bulb globe temperature (WBGT) index be used as a measure of severity of occupational txposures to heat stress.[1] This index had earlier been adopted for guidance of hot-weather training practices in the U. S. Marine Corps.[2] It has also been provisionally recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) as the basis for setting a threshold limit value (TLV).[3]

Among the criteria stated by NIOSH[1] for selecting a suitable index were (1) that the measurements and calculations be simple, and (2) that index values be predictive of physiological strains of heat exposure.

The first criterion is met better by WBGT than by most other indices because for indoor conditions it involves measurements and easy calculation from readings of only two instruments: a 6-inch-diameter blackened sphere provides a globe temperature, t_g, and a stationary thermometer with wetted wick over the bulb provides a natural wet-bulb temperature, t_{nwb}. Then,

$$\mathrm{WBGT} = 0.7t_{nwb} + 0.3t_g$$

(Out of doors and in sunlight, three measurements are required. The recommended formula is $0.7t_{nwb} + 0.2t_g + 0.1t_a$ is air temperature.)
By contrast, analysis in accordance with separate factors affecting heat transfer requires at least four environmental measurements (dry bulb, t_a; psychrometric wet bulb, t_{wb} globe temperature; and wind speed, V) plus more complicated computations.[4]

WBGT levels are regarded as having meanings roughly equivalent to those of the well-known corrected effective temperature scale,[5] which in fact was the intent in developing WBGT (C. P. Yaglou, personal com-

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[†] Professor H. S. Belding, an eminent environmental physiologist, passed away suddenly on August 6, 1973. This contribution is one of his last scientific publications to enrich our literature.

munication, 1960; D. Minard, personal communication, 1972).

Arguments that the two measurements for deriving WBGT should suffice relate to the fact that t_{nwb} not only reflects the effect of humidity on evaporative cooling in a way qualitatively analogous to its effect on man but also gives higher readings when air movement is low or when radiant heat is present. This has recently been demonstrated by Romero Blanco in our laboratory. (*"Effect of Air Speed and Radiation on the Difference between Natural and Psychrometric Wet Bulb Temperatures,* Master's Essay, Graduate School of Public Health, University of Pittsburgh, 1972). The latter deviations seemingly are in the right direction because low air movement (usually) and radiant heat both increase heat strain.

Further, the equilibrium temperature reached by the globe, which is used because of its responsiveness to radiant heat load, is also affected by air temperature and wind speed. At a given radiant heat load, lower wind speed and/or higher air temperature will yield a higher globe temperature reading. These effects also are expected to be appropriate in direction to indicate greater heat strain.[2] The exception to these statements derives from the sometimes deleterious effect of higher air speed when air temperature is higher than skin temperature (35°C, 95°F). In this type of environment, and in the presence of radiant heat, the globe will read lower, whereas the heat stress is actually greater.

It is clear that the two measurements reflect to some degree influences of all four environmental parameters. However, it must be regarded as fortuitous if WBGT as determined from the interaction of environmental effects has uniform connotation regardless of the levels of the four components. In fact, T. F. Hatch (personal communication, 1973) has pointed out that the evaporative coefficient affecting t_{nwb} is about five times that for man because of a large difference in curvature between thermometer and man; even if t_{nwb} readings correctly represented the effect of air movement on evaporation of sweat at one wind speed, they could not possibly be correct at others. There is also documentation that effective temperature (ET) and corrected effective temperature (CET) on which the weighting of t_{nwb} and t_g in the WBGT formula is based, do not predict strain uniformly.[5]

To our knowledge the physiological equivalence of WBGT index readings has never been evaluated under carefully controlled combinations of environmental conditions and work rate. The objective of this study is to test this equivalence under laboratory conditions. Practical considerations necessitated restriction of the present study to four combinations of humidity, radiant heat load, and wind speed at two levels of WBGT and at one level of activity. Air temperature was not a variable and was set equal to anticipated skin temperature—namely, at 35.6°C (96°F); this effectively eliminated convective heat transfer as an avenue of heat exchange for the body.

Experimental Design and Methods

Choice of Work Level and Hot Conditions

A work level was chosen which has been judged a reasonable average limit for an 8-hour shift—namely, 300 kcal (1200 Btu) per hour.[6] To produce this level of energy expenditure the subjects walked on a level treadmill at 5.6 km (3.5 miles) per hour. A duration of 2 hours was specified, which is more than adequate to assure reaching a steady physiological state if environmental conditions did not prevent this.

In its recommendations for a standard for work in hot environments, NIOSH defines "hot environmental conditions" as those that have a WBGT level exceeding 79°F (26.1°C).[1] (Note: Hereinafter, WBGT levels are specified as WBGT in °F.) The ACGIH tentative TLV[3] suggests that this level is critical only for continuous work at a metabolic rate as high as, or higher than, the 300 kcal/hr adopted for this study. If this is correct, the physiological response of heat-acclimatized young men, the participants of our study, to exposure at WBGT 80 (26.7°C) would be minimal. In fact, WBGT 85 (29.4°C) was selected as a limit for active training of U. S. Marine Corps recruits; this limit was shown to confer good protection against heat injury.[2] For later stages of training of limit WBGT 88 (31.1°C) was found to provide protection.

With these considerations in mind, and because we wished to test WBGT at critical levels of strain, we selected WBGT 85 (29.4°C) and WBGT 89 (31.7°C) for this study.

Air temperature was kept at 35.6°C (96°F); deviations from this value did not exceed 0.2°C (0.4°F). Half of the experiments were run without forced air movement (measured wind speed less than 6 m/min [20 fpm]); the other half, at 120 to 130 m/min (~400 fpm). In four of the climatic conditions, the globe and air temperatures were the same; that is, no radiant heat was present. In the other four conditions, a radiant heat load resulting in t_g = 42° to 43°C (~108° to 110°F) was provided. Humidity (ambient water vapor pressure, P_a) was adjusted in each environment to yield the targeted WBGT level. The design resulted in four environmental combinations at each of two WBGT levels, 85 and 89, as shown in Figure 1. (Figure 1 is a nomogram, also useful for rapid determination of WBGT from t_g and t_{wnb}.) Each condition is given an identifying number 1 through 8. Control experiments (*C*) were run in a thermally neutral environment, WBGT 68 (20°C).

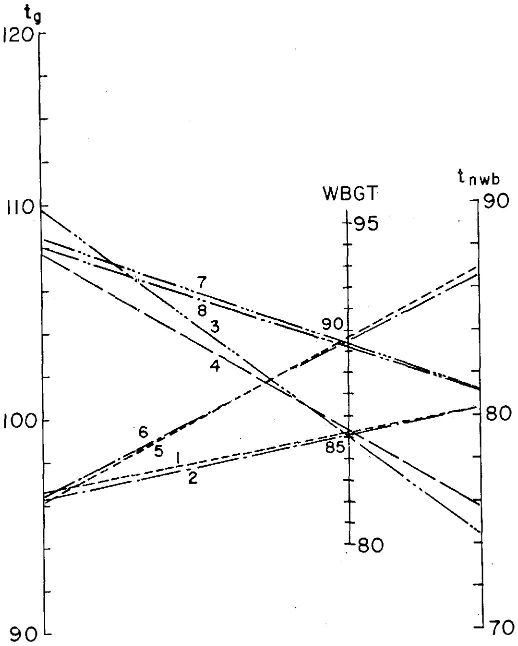

Figure 1. Nomogram showing combinations of t_{nwb} and t_g for the two WBGT levels used in the experiments. t_{air} = 96°F; V = nil or 130 m/min.

Heat Chamber

The men were exposed in a short wind tunnel (67 × 67 × 80 feet) built in a larger room, where thermal conditions could be preset and controlled. The radiant heat source was a bank of ten infrared heaters fixed on one side wall of the chamber, with a reflecting aluminum screen on the opposite wall. While walking on the treadmill the participant was exposed laterally. Radiant heat load was adjusted to the desired level (a level which would not burn the subject's skin in a 2-hour exposure) by variable transformers. A large fan suitably baffled was used to create the high wind speed. For still air conditions, the fan was switched off.

Participants and Procedure

Three fit, young, heat-acclimatized male volunteers were employed for the study. Their physical characteristics are given in Table I. They wore work clothes (cotton khaki long trousers and long-sleeved shirt) as do most men in hot industries where WBGT is ultimately to be applied.

Metabolic rate of the walking subject (M) was determined at 45 and 105 minutes during each exposure by expired gas collection in a Douglas bag and oxygen analysis with a Beckman O_2 analyzer (Model C2). The mean *M* for the three subjects during the

TABLE I

Physical Characteristics of the Participants

Subject	Age (years)	Weight (kg)	Height (m)	Body Surface Area (m^2)
JT	21	59.98	1.671	1.68
KZ	22	64.36	1.818	1.84
MW	22	61.89	1.701	1.71

experimental series was 289 kcal/hr (262 to 315 kcal/hr). The treadmill speed and stepping rate were timed and adjusted in each experiment as an additional check of work rate.

Prior to heat exposure the men rested for about half an hour in cool surroundings, while a rectal probe was inserted, heart rate electrodes were fixed in place, and calibrations were checked. The subject entered the chamber after rectal temperature (t_{re}) and heart rate (HR) were stable. The three subjects were exposed for 2 hours to the same environment on the same day, in sequence. Experimental sessions were on Tuesday through Friday each week, Mondays being kept for boosting the acclimatization level of the subjects by work in a hot enviroment (36°C).

Environmental and Physiological Measurements

The ambient air and psychrometric wet-bulb temperatures were monitored by copper-constantan thermocouples and controlled to the desired level during the experiment. They were also determined with a motor psychrometer (HB Instrument Model 23000) at intervals. At the same time, readings of two globe therometers, two natural wet-bulb thermometers, one Botsford wet-globe thermometer (WGT),[7] and an Alnor Model K thermoanemometer were taken. The instruments were mounted on a stand with the sensing elements 4 to 5 feet above the floor, except that the second globe themometer was 1.5 feet below the first. Prior to each exposure, the instrument stand was located centrally on the treadmill, at the position where the subject would walk. Readings were taken at intervals until stable values were obtained. These, and a series of readings after each test, were used to give an average reading for each observed parameter. When the subject was walking on the treadmill, the instrument stand was moved to one side. While t_g and V were somewhat different in the new position, the variable transformers and air speed settings were not changed.

Heart rate and rectal temperature were recorded continuously on a Beckman Dynograph. As exposure proceeded, the levels rose but had reached steady values for the second hour of most exposures. The forehead skin temperature was measured at 10-minute intervals with a bow thermocouple and potentiometer (Honeywell-Brown).

The subject was weighed nude before and after the experiment to compute the total sweat loss (S gm/hr). He was also weighed clothed inside the chamber at 0, 30, 60, 90, and 120 minutes; these weighings were used to calculate the evaporative water loss. The evaporative water loss in the last two 30-minute intervals were not widely different, and the mean of these values was taken as the evaporative water loss (E gm/hr).

At least one duplicate experiment was conducted in each environment to check reproducibility.

Computations

The WBGT for each experiment was computed according to the formula. Availability of psychrometric data made it possible to compute other heat stress indices. From the observed parameters, values were computed as required for the Belding-Hatch heat stress index (HSI), including M, radiative and convective heat exchanges (R and C), evaporation required ($E_{\mathrm{req}} = M + R + C$), maximum evaporative capacity ($E_{\max}$), using programs on the PDP10 computer. In computing, a mean skin temperature of 35°C (95°F) and skin P of 42 mm Hg were assumed, as the actual values were not determined. Experience in this laboratory has shown that this assumption is justified for the present situation. Further, for the still air conditions, the effective air speed was taken as 54 m/min and not the observed value of 3 to 6 m/min. According to Nishi and Gagge,[8] the effective air movement for a man walking on a treadmill in still air is this high because of the movement of the body and limbs. The predicted 4-hour sweat rate (P4SR in liters)[9] was derived from a nomogram[10] using the observed data for each environmental condition.

Results

The data from a total of thirty-four experiments on the three participants at WBGT 85, WBGT 89, and WBGT 68 were tabulated under three categories: environmental parameters, physiological strain parameters, and heat stress indices. Inspection of the tabulated data showed that adequate reproducibility of experimental conditions had been achieved (WBGT = ±0.75°F) and that the observed physiological responses for the three men were sufficiently similar to justify the presentation in terms of mean values in this report. The data from duplicate runs, where available, have been included in the averages.

A summary of the data is given in Figure 2. The physiological data are presented in the form of histograms; the range of values for the three men is shown. This information pertains to the steady-state condition during the second hour of the exposure, except in one case, condition 5 at WBGT 89. In this condition, two subjects (KZ and MW) completed the exposure, although with considerable difficulty. Rectal temperature and HR were still rising at the end of 2 hours. The third subject (JT) could not continue beyond 71 minutes in one trial in this very humid, still air environment (WBGT 89). His final t_{re} in this exposure had risen to 39°C, and his heart rate had risen sharply in the last 5 minutes to 160 to 165 beats/min from about 140 beats/min. In a duplicate run, he had again to be removed from exposure, this time at 62 minutes.

Discussion

Figure 2 makes it clear that the physiological responses of the subjects were not independent of the combination of t_g, t_{nwb}, and V used. While differences in responses are just detectable at WBGT 85, they are pronounced at the WBGT 89 level. Judged

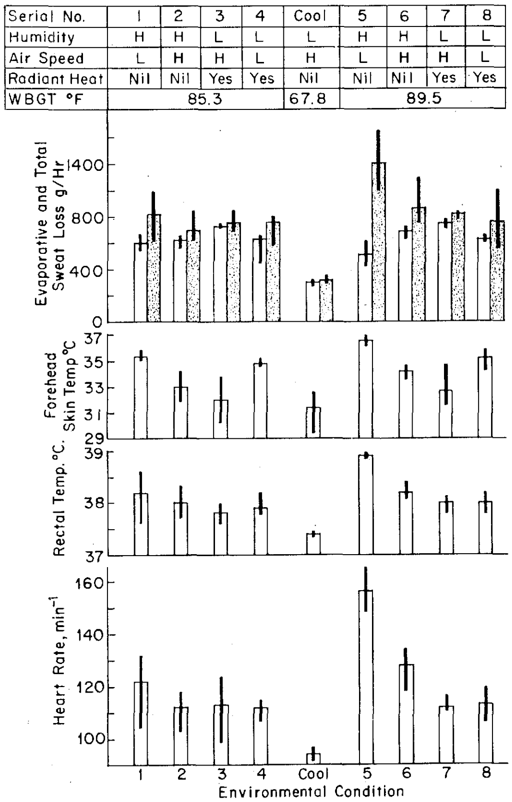

Figure 2. Physiological responses to combinations of t_{nwb} and t_g at WBGT 85 and 89, also in control exposure at WBGT 68. Ranges of values for the three men are shown by heavy lines.

from the observed physiological parameters, the four environmental combinations at each WBGT level could be ranked in order of ascending physiological strain as follows:

1. Conditions 3 and 7 with radiant heat, low humidity, and high air movement produced the least strain.
2. The strain of conditions 4 and 8 with radiant heat, low humidity, and low air movement was about the same as for conditions 3 and 7.
3. Conditions 2 and 6 involved no radiant heat, but high humidity and high air movement; the strain of 2 was not really different from the preceding conditions, but that of 6 was definitely higher.
4. Conditions 1 and 5 involved no radiant heat, but had high humidity, low air movement, and at both levels of WBGT produced more strain than the other conditions.

The strains were greater at WBGT 89 as compared to WBGT 85 for condition 5 against 1, and for condition 6 as against 2. For the other pairs of environmental conditions (3 and 7, and 4 and 8), it is doubtful whether the differences in physiological responses as a result of a 5°F increment in WBGT were real.

Condition 5 was the most stressful environment in this series and resulted in high heart rates (146 to 165 beats/min), rectal temperatures (38.8 to 39°C), forehead temperatures (36.2 to 36.8°C) and sweat rates (1000 to 1453 gm/hr), together with the lowest rates of evaporation (414 to 610 gm/hr). This is the condition in which all subjects evidenced a high level of distress. At WBGT 85 the extra strain of the same relative combination of conditions (condition 1) was perceptible but not large.

With high air speed and high humidity, the strains at WBGT 89 (condition 6) were less than with low air speed, but were still greater than for all remaining environments. In those other conditions, the strain would be regarded as "acceptable" under the proposed NIOSH recommendation and the earlier WHO report[11] which set 38.0°C (100.4°F) as the highest body core temperature permissible for prolonged exposure.

The heart rates under these same five conditions averaged 112 beats/min. While this is 18 beats higher than under the "neutral" control condition, such rates would be considered "marginally acceptable" under the WHO criterion limit of 110 beats/min. None of these five conditions was overly stressful in the view of the three subjects.

Observed sweating levels of 696 to 816 gm/hr were reasonable in view of occupational capacities of fit, acclimatized men to sweat at 1 liter/hr or more.[12] Most of the sweat produced was evaporated, indicating the ability of the environment to accept the heat load associated with these conditions. Common features of conditions 3, 4, 7, and 8 were the high t_g due to radiation. This meant a relatively low t_{nwb} and ambient water vapor pressure.

It will be noted that the apparent stress in terms of sweating and strain in terms of heart rate were not greater in the radiant heat experiments at WBGT 89 (conditions 7 and 8) than at WBGT 85 (conditions 3 and 4). The difference in environmental conditions at the two levels was primarily one of t_{nwb} and humidity rather than heat load. As noted in Table II, actual calculated heat load ($M + R + C$) in condition 7 was essentially the same as for condition 3 (440 versus 466 kcal/hr); for condition 8 it was the same as for condition 4 (339 versus 345 kcal/hr). On the assumption that evaporative capacity was adequate to dissipate the heat load (evidenced by the fact that most of the sweat was evaporated in all four cases), this suggests that the strain should be subcritical and that rectal temperature should not have been raised beyond the permissible 38.0°C (100.4°F) associated with this grade of activity; this was, indeed, the case.

These observations, together with data on the other conditions, seem to indicate not only that a given level of WBGT has meaning dependent on environmental conditions, but

TABLE II

Mean Value of Computed E_{req}, E_{max}, HSI, HSI', P4SR, and Observed Botsford Wet-Globe Readings for the Different Environmental Conditions

WBGT Level		85°F				68°F	89°F			
Condition	*Units*	1	2	3	4	C	5	6	7	8
Metabolic Rate (M)	kcal/hr	290	297	287	290	288	290	297	280	285
Radiative Heat Exchange (R)	kcal/hr	7	7	172	51	−35	4	3	153	51
Convective Heat Exchange (C)	kcal/hr	3	7	7	4	−87	4	7	7	3
E_{req} (M + R + C)	kcal/hr	300	311	466	345	166	298	307	440	339
Maximum Evaporative Capacity (E_{max})	kcal/hr	249	380	565	376	662	155	232	436	300
E'_{max}	kcal/hr	327	499	741	493	869	203	304	572	394
HSI		120	81	84	91	25	197	133	100	114
HSI'		92	62	63	70	19	147	101	77	89
P4SR	liters/4 hrs	3.7	3.3	4.3	4.0	2.0	8.6	3.9	4.7	4.7
WGT	°F	82	80	76	78	64	86	86	82	83
Apparent Strain		mod.	little	little	little	none	very high	mod.	little	little

that higher levels on the WBGT scale do not always signify greater strain, especially when the environment is relatively dry.

Some of these inconsistencies have been pointed out in respect to the ET and CET scales, from which WBGT was derived.[5] In the zone of evaporative regulation, ET and CET have been found to understress the adverse effect of humidity; this is especially so when the environmental conditions approach the tolerance limit.[13-15] Lind and Hellon[15] have demonstrated that the physiological responses and tolerance times of resting, nude, acclimatized man were more in dry environments (relative humidity 45%) than in wetter conditions (relative humidity 85%) at the same ET. This finding is similar to the present observation on clothed, working men. It has also been reported that physiological responses at lower ET levels were similar in both humid and less humid conditions,[16] a situation which was approximated here in the case of WBGT 85. ET scales are considered to be misleading at high heat stress levels; Leithead and Lind[10] state that it has "an inherent error that increases as the severity of the environmental conditions increases." McArdle *et al.*[9] also point out that the ET scale does not adequately reflect the deleterious effects of low wind speeds in humid environments. When wind speed is appreciable (30 to 100 m/min), it is claimed that the ET scale overemphasizes the stress due to high air temperatures.[12,17] Yaglou *et al.*[18] have pointed out that, when $t_g = t_a$, t_g value will not show any cooling effect of wind. Even so, the t_{nwb} component of WBGT will respond to wind effects.

It is thus not surprising that WBGT index values failed to parallel the physiological strains in these environments of varying humidity, air speed, and radiant heat. In short, the demonstrated inconsistencies of ET are perpetuated in WBGT.

HSI, P4SR, and Botsford Globe Temperature

As a secondary objective of this study, values of these other indices were derived for the eight conditions. In Table II, calculated values of the heat load $(M + R + C)$ are given in accordance with Hatch,[19] modified by Hertig and Belding[20] for clothed men. The value of E_{max} was apparently less than $(M + R + C)$ in conditions 1, 5, 6, and 8.

The HSI index values differentiate between the conditions in correct order of physiological strain, although the resulting strains seem to be overemphasized. Belding and Kamon[21] have recently reported a new, larger coefficient for $E_{\max}$ for clothed men. We have designated values calculated with this new coefficient as $E'_{\max}$ and HSI′. When $E'_{\max}$ is used, HSI′ values equate better than HSI with the observed strain. One anomaly exists, in that condition 1 which resulted in moderate physiological strain had the same HSI′ as condition 8 which actually was less severe.

Readings of the Botsford globe (WGT) have not yet been assigned clear meanings in terms of physiological strain, although some correlations with other indices have been demonstrated.[22] It will be noted in this study that the relation between WGT and strain was partially satisfactory. The Botsford globe did not differentiate between conditions 5 and 6, which had widely different effects on the participants. Hatch[23] has discussed the reason for the limitation of the Botsford globe; this he associates with the small diameter of this globe.

The P4SR values for the eight conditions do not correspond very well with the physiological strain. This index exaggerates the potential strain in conditions where radiant heat is prevalent. The P4SR values for the radiant heat conditions 3, 4, 7, and 8 are higher than for conditions 1 and 6, which were clearly more strenuous physiologically. Actually, predicted sweat rates are far in excess of the observed sweat rates.

Practical Interpretation of WBGT Results

Although the present study is restricted to one air temperature and work level and three fit men, the results amply demonstrate that the same WBGT index value does not have consistent physiological meaning independent of the environmental parameters. Higher air temperatures and work rates would be expected to exaggerate these inconsistencies. But are these inconsistencies of practical importance? An environmental vapor pressure of 30 mm Hg was used in conditions 5 and 6 at WBGT 89. This condition can exist in Southeastern United States in the summertime, in many tropical areas of the world, and in special occupations like deep mining, operating laundries, and galvanizing metal. Thermal radiation levels and variations in wind speed as wide as were used are commonly encountered. WBGT 89 produced excessive strain for prolonged exposure at this work level, when the humidity was high, but not when the air was relatively dry. Another practical problem relates to the finding that the strains of WBGT 85 and 89 were not different under dry conditions. These levels of WBGT are presumed to be in the range that is critical for well-being of workers; yet the scale does not consistently signal deleterious environmental combinations. Further, while it may be justified to set some such level as WBGT 80 to 82 as a warning of critical conditions in humid environments, the use of the same level for this purpose in dry environments seemingly would be overcautious on the basis of likely strain. A solution to this difficulty which merits consideration might be to establish two sets of WBGT limit levels, one for humid and the other for dry condition.

Perhaps in this way the NIOSH criterion that the index of choice should "have a valid weight in relation to total physiological strain" might be satisfied by the WBGT index.

Conclusion

Environmental combinations which yielded the same WBGT levels (WBGT 85 or 89) resulted in different physiological strains in individuals working at a moderate level. The index failed to differentiate between humid conditions which proved strenuous and dry environments which did not result in execessive physiological strain. Further, a more serious inconsistency was that a higher WBGT level did not in dry environments produce greater strain than similarly dry environments at a lower WBGT level. WBGT, therefore, has limited value as a predictor of physiological strain at the higher heat stress levels which may be encountered in industry.

Acknowledgments

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