6.5

AN EVALUATION OF SEVERAL WET BULB GLOBE TEMPERATURE ALGORITHMS AT DUGWAY PROVING GROUND

Margaret B. Curtis* and Frank W. Gallagher III

U.S. Army Dugway Proving Ground, Dugway, UT

1. INTRODUCTION

The Wet Bulb Globe Temperature (WBGT) is a standard heat-stress measure used by the U.S. Army. The parameter is created by an arithmetic combination of measurements from standard air-temperature sensors, black globe temperature sensors, and natural wet bulb temperature sensors. The natural wet bulb sensor requires, especially in the desert environment, nearly daily maintenance to fill the reservoir and to change the wick. As a result, only one or two locations around the test range can have an in situ direct measurement of the WBGT. Test and training activities occur at many locations, so a calculation of the WBGT, using standard meteorological variables, is required.

WBGT is used by the U.S. Army to regulate soldiers physical training and fluid intake in order to avoid heat exhaustion of soldiers. In 1957, Yaglou and Minard developed the wet bulb globe temperature as an indicator of potential heat stress for soldiers training at the U.S. Marine Corps Recruit Depot on Parris Island in South Carolina. Humidity in this region can be quite high and Marines have to undergo vigorous training exercises in military clothing, typically under full sun. There is a significant risk of heat injury if training or work is not limited under high heat and humidity conditions. Scientists later used the WBGT for other applications such as an easily measured, general heat-stress index. In time, the use of WBGT widened and is often incorporated within Occupational Safety and Health Administration (OSHA) guidelines for working in hot environments. The WBGT is defined as:

$$WBGT = 0.7T_n + 0.2T_g + 0.1T_a$$

$$WBGT = 0.7T_n + 0.3T_g$$

for outdoor and indoor work, respectively, where T_n is a natural wet bulb temperature, T_g is the black globe temperature, and T_a is the ambient (dry bulb) temperature.

In the field, WBGT is measured by a set of three thermometers: one is shaded and provides the ambient temperature, the second has the bulb in a black sleeve which results in the black globe temperature, and a third is shrouded in a moistened wick exposed to the wind and sun to yield the natural wet bulb temperature. Simple calculation of these readings yields the WBGT. Table 1.1 indicates the color coded scale and unacclimatized actions used with various scales of WBGT.

HEAT CONDITION	WBGT INDEX F	UNACCLIMATIZED
1	<82	Use caution in planning extremely intense physical exertion.
2 GREEN	82-84.9	Use discretion in planning heavy exercise.
3 YELLOW	85-87.9	Suspend strenuous exercise during the first 3 weeks of training. Activities may be continued on a reduced scale after the 2d week. Avoid activity in the direct sun.
4 RED	88-89.9	Curtail strenuous exercise for all personnel with less than 12 weeks of hot weather training.
5 BLACK	90 & up	Suspend physical training and strenuous exercise. Essential operational commitments (e.g., guard duty) will not be suspended.

Table 1.1 The following table, slightly modified for clarity, is from the Army Training and Doctrine Command (TRADOC) Reg. 350-29. The regulation states, "Heat conditions are classified by color (green, yellow, red, and black) in increasing order of heat stress according to WBGT readings. Commanders must adapt training/physical activity and uniform requirements to conform with the precautions for each heat condition listed."Note that body armor or protective clothing adds 10 degrees F to the WBGT index.

The measurement of the black globe and natural wet bulb temperatures are not typically available at the Dugway Proving Ground (DPG) Surface Atmospheric Measurement System (SAMS) sites, so an alternative method of determining the WBGT is required in order to evaluate the WBGT across the range.

The purpose of this project is to evaluate alternative WBGT calculations methods which do not require natural wet bulb temperature or black globe temperature.

---

*corresponding author address: Margaret B Curtis, TEDT-DPW-MEM 4053 A Street MS#6, Dugway, UT 84022 email: margaret.curtis@us.army.mil

2. Data

2.1 Instrumentation

In order to measure the WBGT, three different sensors are required. In our study, the air temperature was measured using a calibrated temperature/relative humidity probe (either a Campbell Scientific CS-500 probe or a Vaisala HMP-45C probe. The black globe temperature was measured by a thermocouple mounted in the center of a flat black painted, copper, oval-shaped fishing buoy. The thermocouple was a T-type (copper-constantan) junction with the second junction provided by the Campbell Scientific CR-23X datalogger. The natural wet bulb (T_N) sensor consisted of a type-T thermocouple covered by a wet wick exposed to the natural wind flow and fed by water contained a PVC reservoir. (see Fig 2.1) The reservoirs were typically filled on a weekly basis. However, during a portion of the experiment, there were several occasions when the reservoirs ran dry. An algorithm in the Quality control (QC) program was designed to detect such a fault and such erroneous data were not used in the analysis.

Three identical sets of instruments were deployed near the DPG meteorology center to provide a point of reference for the variability of the WBGT measurements.

Fig 2.1 Black Globe and Natural Wet Bulb sensors used at Dugway Proving Ground

2.1 Quality Control

Several procedures were performed to insure only accurate data were included in the analysis. Times in which maintenance was performed were eliminated from the data set to prevent the inclusion of error when stations were undergoing maintenance. The maintenance consisted primarily of replacing the wet bulb wicks and refilling the reservoirs with de-ionized water. Secondly, range checks were performed on all sensors; data outside these gross QC ranges were eliminated. (see Table 2.1) Statistical range checks were also performed and data outside three standard deviations were eliminated. Next, gradient checks were performed to eliminate data within time periods where sudden, unnatural jumps occurred in the data. Finally a check was made that the T_n sensor was not dry, which was determined by the difference being more than 2^{o}C between the T_N and T_a.

WBGT Sensor QC Checks	
QC Check	*Valid Range of Data*
Range Checks	$-40°C \le$ Temperature $\le 50°C$ $0 \le$ RH $\le 103\%$ $-50 \le$ Solar radiation ≤ 1300 Wm^{-2} $600 \le$ pressure ≤ 1200 hPa $-40 \le$ BG_Temp $\le 75°C$ $-40 \le T_n \le 50°C$
Gradient Checks	$\frac{dT}{dt} \le 5^\circ C\, s^{-1}$ $\frac{d(RH)}{dt} \le 10\,\% s^{-2}$ $\frac{d(SRAD)}{dt} \le 200\, Wm^{-1}s^{-1}$ $\frac{d(press)}{dt} \le 50\, hPa$ $\frac{d(BG\_Temp)}{dt} \le 5^\circ C s^{-1}$ $\frac{d(NWET\_Temp)}{dt} \le 5^\circ C s^{-1}$

Table 2.1 Quality Control parameters

3. Results

Several methods were evaluated as potential predictors of WBGT at stations that record standard meteorological measurements. These methods include an algorithm developed by the Department of Energy (3.1), and multiple linear regressions of the standard predictors using both Dugway and White Sands Missile Range (WSMR) data (3.2) .

3.1. Assesement of Savannah River Temperature Algorithm

The algorithm used in this experiment was a slightly modified version of the equations developed by Hunter and Minyard (2000) for use at the Department of Energy's Savannah River Site (SRS) in South Carolina. The SRS WBGT estimate uses only traditional meteorological measurements: dry bulb temperature, relative humidity, solar radiation, and wind speed. After evaluating a summer season of data from the SRS Central Climatology site, Hunter and Minyard (2000) developed the following approximation of the natural wet bulb temperature using multiple linear regression of data taken from the SRS:

$$T_n = T_w + 0.0021S - 0.42u + 1.93$$

where T_n is the calculated natural wet bulb temperature (°F), T_w is the psychrometric wet bulb temperature (°F), u is the wind speed (ms^{-1}), and S is the solar irradiance (Wm^{-2}). Since the SAMS stations do not measure the psychrometric wet bulb temperature, we had to calculate that value using variables measured by the station (e.g. temperature, relative humidity, pressure) using standard methodologies.

Our initial investigation of the accuracy of this relationship revealed that it is clearly designed to work in an environment different from DPG. The relationship holds fairly well at rather low T_n temperatures (< 14°C) but the calculated T_n temperature is still too low, often 2°C too low. At warmer T_n temperatures, the error becomes unacceptably large with the calculated value being nearly 8°C too low. By looking at a time series of the measured T_n temperatures and the SRS-calculated T_n temperatures (Fig 3.1), we see that the largest differences occur during the warmer part of the day. Also, for this event, the largest difference (~1600 LT) occurred with the strongest winds.

3.2 Multiple Linear Regression

Since the T_N temperature makes up 70% of the WBGT value, it is important to get the most accurate-calculated value of T_n possible. We performed a multiple linear regression of the Station 1 one-second data for 28 June 2004 using the following parameters: wet bulb, solar radiation, wind speed, and relative humidity. The best-fit equation was calculated to be:

$$T_n = 0.90397T_w + 0.00147S - 0.01807u$$
$$- 0.08996RH + 6.35396$$

where T_n is the computed T_n temperature (°C), S is the solar radiation (Wm^{-2}), u is the mechanical wind speed (ms^{-1}), and RH is the relative humidity (%).

Although all of the variance of the T_n data were not captured, the results of the regression are encouraging. While there are still differences between the measured T_n and the calculated T_n, the differences are typically less than 2.5°C and the overall data set average difference is 0.00014°C. In order to capture the best regression fit, we need to compute a T_n regression equation for each site, or at a minimum, for each range.

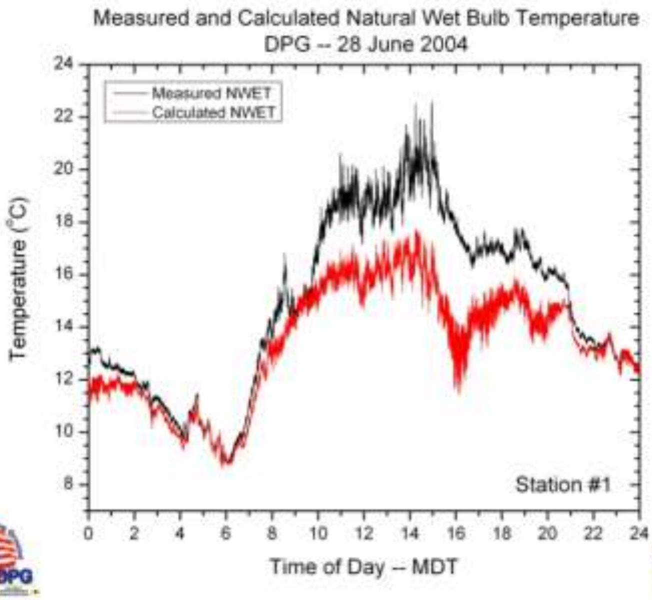

Fig 3.1 Diurnal pattern of predicted vs observed Natural Wet Bulb temperatures at Dugway Proving Ground.

Having demonstrated that a regression developed for SRS is inadequate for use at DPG, a further examination was made of the potential for multiple linear regression (MLR). Identical quality control procedures were implemented (as discussed in section 2.1). MLR was this time done for the WBGT itself (rather than T_n) using the four predictor variables: temperature, relative humidity, wind speed, and solar radiation, which are readily available at locations across Dugway Proving Ground.

In order to asses the utility of the MLR as an approximation to WBGT, several statistics including the Root Mean Square error (RMS) and R^2 value were calculated to determine the goodness of fit (see Table 3.1). It is desirable that the RMS error be less than 1.5°C, the span of a color categorization of WBGT, to minimize the occurrences where the WBGT MLR mis-categorizes the color-coded conditions.

RMS error	1.3233 °C
R^2	0.9277
p-value	1.8
F statistic	9649.5

Table 3.1 DPG regression statistics

The MLR equation for WBGT was found overall to be a good approximation over the entire temperature range. The R^2 value was 0.9277, indicating that most of the observed variance is explained by the predictor variables. The residuals for the regression remain near zero for most of the dataset. There is a slight positive bias in late August. For each of the four dependent variables there is no statistically significant correlation between the residuals and the variables indicating there is no one source of the slight positive bias seen in the last portion of the data.

While the fit of the MLR to the data in general is important, of particular importance is the accuracy of the MLR during conditions where the WBGT is greater than 82°F ('green') since it is under these conditions that changes in work and fluid intake must occur. An examination of the residuals as a function of WBGT color code is presented in Figure 3.1. There is a higher bias (closer to 2) in instances where the WBGT has reached 'green' color threshold indicating that, while the performance over a wide range of temperatures is near the level of accuracy desired, the performance of the DPG MLR within the range of critical interest (green and above) fails to meet our criterion of RMS< 1.5°C. It is however, noted that only three (3) days of condition 'red' were observed in our summer season dataset from DPG which may not provide sufficient data for the MLR to generate accurate predictions

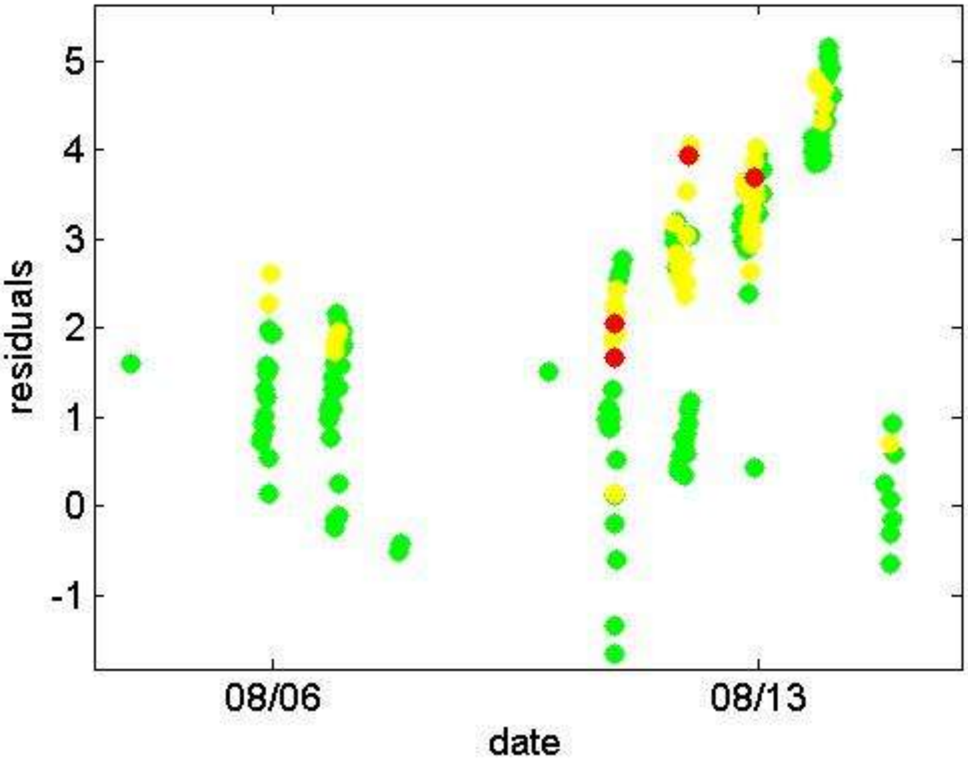

Figure 3.2 DPG regression residuals as a function of date and WBGT color category for green (82°F-85°F), yellow (85°F-88°F), and red (88°F-90°F) conditions

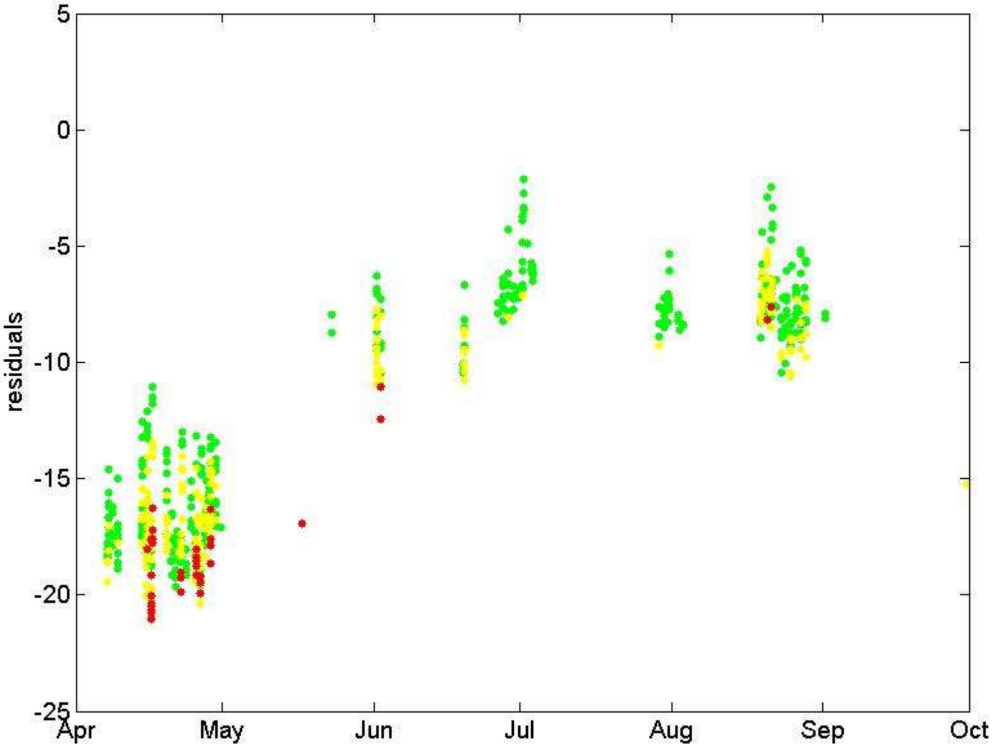

Figure 3.3 comparison of the residuals (DPG predicted- observed) for 3 years of WSMR data

3.2.1 Evaluation of DPG algorithm at White Sands Missle Range

In order to assess the accuracy of the MLR results over a wide range of conditions, a comparison between DPG and White Sands Missile Range (WSMR) WBGT data was made. Data were available from WSMR for the summers of 2003-2005. WBGT was measured every minute while other meteorological variables were reported as 15 min averages from the SAMS at 00, 15, 30, and 45 minutes after the hour. WSMR was chosen as a location because it is a similar elevation and desert environment to Dugway, but experiences higher frequency of 'red' condition days.

In addition to the quality control procedures described in 2.1, quality control of the WSMR data included eliminating periods in the early spring and fall when WBGT sensors were not being maintained and reporting unreasonably high values (e.g. 49^{o}C in April).

Figure 3.3 depicts the residuals of DPG-MLR applied to WSMR as a function of color code. The cold bias in the regression prediction is visible for all color categories and is worse for the yellow and red conditions than the green. Thus, while it appears that DPG-MLR is a more acceptable fit for DPG data, it clearly cannot be applied elsewhere even in regions of similar climate such as the high desert of WSMR

Since WSMR has a higher number of observations in the color coded WBGT temperature ranges of greatest concern, a MLR of the WSMR data was performed to assess the impact of including more data points in a higher WBGT range on the accuracy of the MLR prediction at both WSMR and DPG. To evaluate the utility of adding WSMR data, the RMS error is considered for various combinations and conditions in Table 3.2 and 3.3.

Overall, the RMS error was found to increase for all cases by adding the additional data source. Even when considering only the high temperature data, which was one of the motivating factors for including WSMR data, little to no improvement is seen in the RMS error.

,

		Regression		
		DPG	WSMR	DPG+WSMR
Data Source	DPG	1.33	2.0562	1.8349
	WSMR	6.0768	2.9598	2.9989
	DPG+WSMR	4.3600	3.9850	2.7744

Table 3.2 RMS error for all data

		Regression		
		DPG	WSMR	DPG+WSMR
Data Source	DPG	2.6491	2.6808	2.8153
	WSMR	11.3780	10.5456	10.4840
	DPG+WSMR	10.1438	9.4150	9.3695

Table 3.3 RMS error for 'green' or higher WBGT conditions

4. CONCLUSION

The results of our study show that current algorithms for computing the WBGT from standard meteorological measurements are insufficient for use at Army test ranges. While MLR of WBGT produced high R^2 values, the accuracy of the predictor decreases at the higher more critical temperatures. MLR of the natural wet bulb sensor following the Savannah River Site resulted is under prediction particularly during peak hours.

Overall more work Is needed to accurately calculate the WBGT from alternate sources. Future work includes an analytic solution to the natural wet bulb temperature based upon heat transfer through the wick, and a categorical method of prediction.

Bibliography

TB MED 507, Technical Bulletin Medical 507, *Heat stress control and heat casualty management.* Hq, Department of the Army and Air Force 7 March 2003.

Hunter, C.H., and C.O. Minyard, 2000: Estimating wet bulb globe temperature using standard meteorological measurements, Preprints Second Symp. Env. Appl., 9-14 January 2000, Long Beach, CA, 61-66.

Occupational Safety & Health Administration (OSHA), 01/20/1999, U.S. Department of Labor, OSHA Technical Manual TED 1-0.15A, Section III, Chapter 4: Heat Stress. http://www.osha.gov/dts/osta/otm/otm_toc.html

Yaglou, C.P. and Minard, D. (1957) Control of heat casualties at military training centers. *Arch. Indus. Health* 16:302-305.