WSRC-MS-99-00757

2.7 ESTIMATING WET BULB GLOBE TEMPERATURE USING STANDARD METEOROLOGICAL MEASUREMENTS

Charles H. Hunter*
Westinghouse Savannah River Company, Aiken, South Carolina

C. Olivia Minyard
College of Charleston, Charleston, South Carolina

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available for sale to the public, in paper, from: U.S. Department of Commerce, National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161,
phone: (800) 553-6847,
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Available electronically at http://www.doe.gov/bridge
Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:
U.S. Department of Energy, Office of Scientific and Technical Information, P.O. Box 62,
Oak Ridge, TN 37831-0062,
phone: (865)576-8401,
fax: (865)576-5728
email: reports@adonis.osti.gov

1.

The heat stress management program at the Department of Energy's Savannah River Site (SRS) requires implementation of protective controls on outdoor work based on observed values of wet bulb globe temperature (WBGT). Through the mid 1990s, WBGT data were collected manually several times daily with a portable instrument, and the results were disseminated to onsite workers via telephone. Subsequent workforce reductions adversely affected the ability of the SRS industrial hygiene department to continue routine WBGT measurements. To ensure continued compliance with heat stress program requirements, a computer algorithm was developed which calculates an estimate of WBGT using standard meteorological measurements. In addition, scripts were developed to generate a calculation every 15-minutes and post the results to an Intranet web site.

An evaluation of this algorithm has shown that the results are fully adequate to support programmatic requirements. Furthermore, automatic generation of WBGT information has proven to be a highly effective means of communicating potentially hazardous conditions to the general workforce in real-time.

2. BACKGROUND

2.1 General

The SRS is a 300 square mile reservation located in south central South Carolina, just east of Augusta, GA. Historically, the primary mission of the SRS was the production of nuclear materials for national defense. This required the operation of multiple facilities designed to fabricate, irradiate, and chemically separate nuclear fuel and target elements. Although the production mission has waned in recent years, ongoing operations include nuclear materials storage and disposition, management of high-level nuclear and mixed waste, and environmental restoration. Much of the work involving waste management/environmental restoration must be conducted outdoors, and, in some cases, requires the use of protective clothing. Other outdoor work conducted at SRS includes facility construction and maintenance, aquatic and ecological research and management of approximately 170,000 acres of forest.

2.2 *The SRS Heat Stress Management Program and WBGT*

The American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLV) for heat exposure provide the basis for heat stress management at SRS (WSRC, 1995). These TLV's are based on observed values of WBGT, which is defined as:

$$WBGT = 0.7T_n + 0.2T_g + 0.1T_a \qquad (1)$$

where T_n is a 'natural' (static) wet bulb temperature, T_g is a 'globe' temperature, and T_a is the ambient (dry bulb) temperature.

The natural wet bulb temperature is commonly measured with a thermometer that is covered with a moist, white muslin wick and exposed to the atmosphere without ventilation or shielding, i.e., fully subject to gains and losses of heat through evaporation, solar radiation, and convection. Similarly, T_g is measured with a temperature probe placed in the center of a blackened, hollow copper sphere. The globe thermometer is also passively exposed to the ambient environment.

Neither T_n nor T_g represents perfectly the heat load on a clothed human body. Therefore, the WBGT heat stress 'model' is expressed as a weighted sum of these apparent temperatures. The respective weights are based on correlations with observed deep body temperature and other physiological responses to heat (ACGIH, 1995). In practice, values of WBGT are used to determine one of six heat stress categories. Each category, in turn, defines a prescribed work/rest regimen for outdoor activities.

Prior to the summer of 1996, WBGT measurements at SRS were conducted with a portable, manually operated commercial device. This device consists of a natural wet bulb thermometer, a globe thermometer, and a dry bulb thermometer incorporated in a single hand-held unit. A processor within the device automatically interrogates each of the three temperature sensors every few seconds, processes the data, and outputs a WBGT value on an LCD display. Operating procedures required that measurements be taken several times per day from May through September (WSRC,1995) so workers could call and obtain reasonably current WBGT information for planning outdoor work. Workforce reductions at the SRS during the mid 1990s adversely affected the availability of technicians needed to support this data collection effort. As a result, an investigation of the feasibility of automating WBGT measurements was begun.

Two options for automating WBGT data collection were examined: (1) incorporate a portable WBGT device into the existing SRS meteorological monitoring system, and (2) use available real-time meteorological data to calculate an estimate of WBGT. The former option was determined to be impractical due to the time and costs associated with fabrication of a computer system interface for the device as

---

* Charles H. Hunter, Westinghouse Savannah River Co., Bldg. 773-A, Aiken, SC 29805; e-mail: chuck.hunter@srs.gov

well as the labor that would yet be required to maintain proper operation of the natural wet bulb thermometer. Therefore, it was decided to pursue the latter option.

2.3 *Meteorological Monitoring at SRS*

To support environmental compliance and emergency response activities at SRS, a comprehensive meteorological monitoring program was established during the 1970s. Currently, measurements of wind direction, speed, temperature, and dew point are collected from instruments mounted at two levels on a network of eight 61-meter (m0 towers across the SRS (Fig. 1). A ninth tower near the geographic center of SRS is instrumented with wind, temperature, and dew point sensors at four levels (2m, 18m, 36m, and 61m). This monitoring site, known as Central Climatology (CLM), is also equipped with an automated rain gage, a barometric pressure sensor, and a solar radiometer near the tower at ground level. A data logger at each of the nine towers records a measurement from each sensor at 1-second intervals. The 1-second data are used to calculate 15-minute averages, which are subsequently transmitted electronically to a central computer system for archival in a relational database.

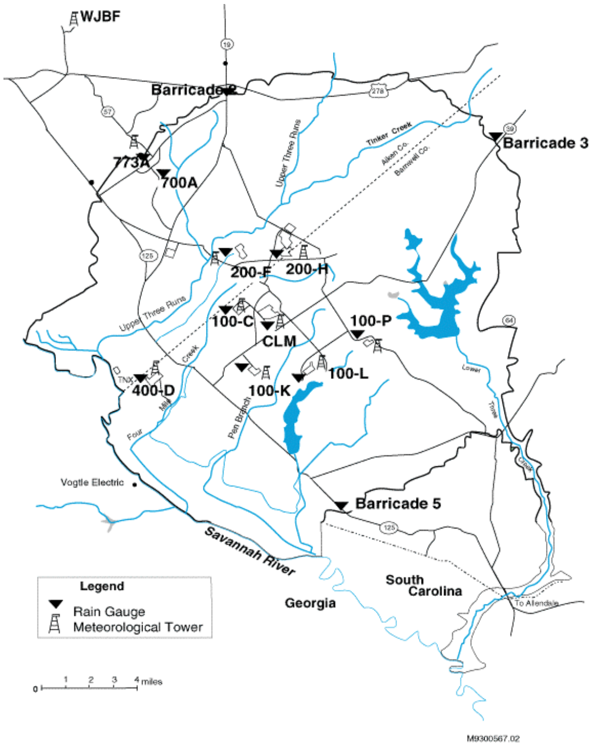


Figure 1. Map of the SRS Indicating Meteorological Tower Locations

3. DEVELOPMENT OF THE WBGT ALGORITHM

3.1 Natural Wet Bulb Temperature, T_n

An examination of WBGT data collected manually during the summer of 1995 provided several insights on the behavior of T_n. First, T_n was always bounded by the standard psychrometric wet bulb, T_w, and T_a. The effects of sunlight on T_n appeared to be relatively small, i.e., the white wick reflects much of the incoming solar energy. Furthermore, T_n tended to approach T_w if the wind speed was equal to or greater than the airflow across a standard ventilated instrument used to determine T_w such as an aspirated dew point hygrometer or sling psychrometer. Alternatively, if conditions were not conducive to evaporation (light winds and high humidity), the natural wet bulb depression, (T_a-T_n), tended to be less than that which occurs under breezy conditions, and, in some cases, appeared to approach values that were one-third to one-half a standard wet bulb depression.

Following a qualitative review of biometeorological indices documented by Driscoll (Haughton and Driscoll 1985), an expression known as the temperature-humidity index (THI) was selected as a potential approximation for T_n. The THI is given by

$$\mathrm{THI}(°\mathrm{C}) = 0.4\,(T_a + T_w) + 4.8 \qquad (2)$$

An inspection of Eq. (2) shows that the THI is only slightly less than an average of T_a and T_w over a range of temperatures of concern for heat stress (greater than 27°C) and, therefore, would provide conservative estimates of T_n in most situations. As noted previously, T_n can be expected to approach T_w for ambient wind speeds equal to or greater than the ventilation rate of an aspirated device used to determine T_w. Therefore, if conditions are breezy and T_a is much greater than T_w (daylight hours, clear skies, and relatively low humidity), the THI considerably overestimates T_n. For conditions characterized by low wind speeds and relatively high humidity, the THI provides a better, although still somewhat conservative, approximation of T_n. Subsequent experience with the THI confirmed this qualitative assessment.

An improved method for estimating T_n was recently developed using data from a series of field measurements conducted over nine days in May, June, and July, 1999. Values of WBGT and the corresponding component temperatures were recorded at 15-minute intervals during a 4-6 hour period between 9AM and 3PM each study day. The study days were chosen to provide data for a range of conditions that are experienced during the warm season, i.e., moderate to high humidity, low to moderate cloud cover, and low to moderate wind speed. All data were collected at the Central Climatology facility.

An analysis of variance was performed on the data to determine the relationship between measured values of T_n and 15-minute average meteorological data from Central Climatology. As expected, nearly 70 percent of the variance in the difference between T_n and T_w was explained by wind speed and solar radiation. A multiple linear regression was run on the data, resulting in the following predictive expression for T_n:

$$T_n = T_w + 0.021S - 0.42u + 1.93 \qquad (3)$$

where S is solar irradiance (W/m^2) and u is wind speed (m/s).

3.2 Globe Temperature

Globe temperature, T_g, is calculated explicitly using the expression

$$(1-\alpha_{sps})\overset{[1]}{S(f_{db}s_{sp}+(1+\alpha_{es})f_{dif})} + \overset{[2]}{\varepsilon_a(1-\alpha_{spl})\sigma T_a^4}$$

$$= \overset{[3]}{\varepsilon\sigma T_g^4} + \overset{[4]}{0.115u^{0.58}(T_g-T_a)} \qquad (4)$$

The two terms on the left side of Eq. (4) represent the sum of short and long wave radiant energy absorbed by the globe, respectively. Solar radiation, S, striking the earth's surface consists of direct beam (db) radiation from the sun and diffuse (dif) radiation reflected by clouds and other atmospheric constituents. For high solar angles (midday) and cloudless skies, approximately 75 percent of the total incoming solar energy consists of direct beam radiation and the remaining 25 percent diffuse radiation (Oke, 1978). The contribution of diffuse radiation to the total solar load increases with increasing cloudiness and haze and with lower solar angles. Since summer afternoons at SRS are frequently hazy with some cloudiness, the average fractional contribution of direct beam radiation, f_{db}, and diffuse radiation, f_{dif}, were assigned values of 0.67 and 0.33, respectively.

Real-time values of solar irradiance, S, are measured at Central Climatology by a radiometer that is level with respect to the horizontal plane (i.e. the earth's surface). The spatially averaged direct beam irradiance on any three dimensional object can be related to measured values of S by determining a shape factor, s, for the object. For a sphere (globe), the shape factor is defined as the ratio of the area of a shadow projected on the horizontal plane to the surface area of the sphere, or

$$s_{sp} = \pi r^2/(4\pi r^2 \cos(z)) = 1/(4\cos(z)) \qquad (5)$$

where z is the solar angle to zenith.

Diffuse solar radiation is isotropic, that is, emitted (or received) equally in all directions. Therefore, the diffuse solar radiation measured by a radiometer is equal to that received by the upper hemisphere of the globe. The lower hemisphere of the globe also will receive short-wave radiation reflected from the ground and nearby low structures. The albedo, α_{es}, for grassy surfaces ranges from 0.15 to 0.25. A value of 0.2 was assumed for this calculation.

The second term on the left of Eq. (4) is the long-wave (thermal) black-body radiation emitted by (received from) a moist, cloudless atmosphere of temperature T_a and thermal emissivity ε. Thermal emissivity, a function of atmospheric water vapor, is calculated from the empirical formula

$$\varepsilon_a = 0.575 e_a^{(1/7)} \qquad (6)$$

where e_a is atmospheric vapor pressure (Oke, 1978). Real-time values of e_a are determined from the expression

$$e_a = \exp\left((17.67T_d / (T_d + 243.5) - 17.67T_a / (T_d + 243.5)\right) \times (1.0007 + 0.00000346P) \times 6.1121\exp(17.502T_a/(240.97 + T_a)) \qquad (7)$$

where P is the barometric pressure. The Stefan-Boltzmann constant, σ, in Eq. (4) is equal to 5.67 X 10-8 ($Wm^{-2}K^{-4}$). Imperfections in the black matte finish of the globe thermometer will cause small amounts of radiation striking the surface of the sphere to be reflected back to the atmosphere. Globe albedo for short and long wave radiation, α_{sps} and α_{spl}, respectively, were assigned a value of 0.05 (Kuehn, 1970).

The two terms on the right side of Eq. (4) represent total radiant energy lost by the globe. The first term expresses long-wave black body radiation emitted from a globe at temperature T_g. The thermal emissivity, ε, for a globe of black matte finish was assumed to equal 0.95 (Kuehn, 1970). The second term on the right is an empirical expression recommended by Kuehn (1970) for the net convective heat loss (or gain) from a sphere of temperature T_g (°C) immersed in air of temperature T_a (°C) moving at a speed u (m/hr).

Equations (4) - (7) are evaluated using real-time 15-minute averages of S, T_a, T_d, P, and u from Central Climatology. An iterative procedure is used to determine the value of T_g that satisfies the equilibrium condition.

Computed values of T_n and T_g are used with observed 15-minute averages of T_a to determine WBGT according to Eq. 1.

4. EVALUATION OF THE WBGT ALGORITHM

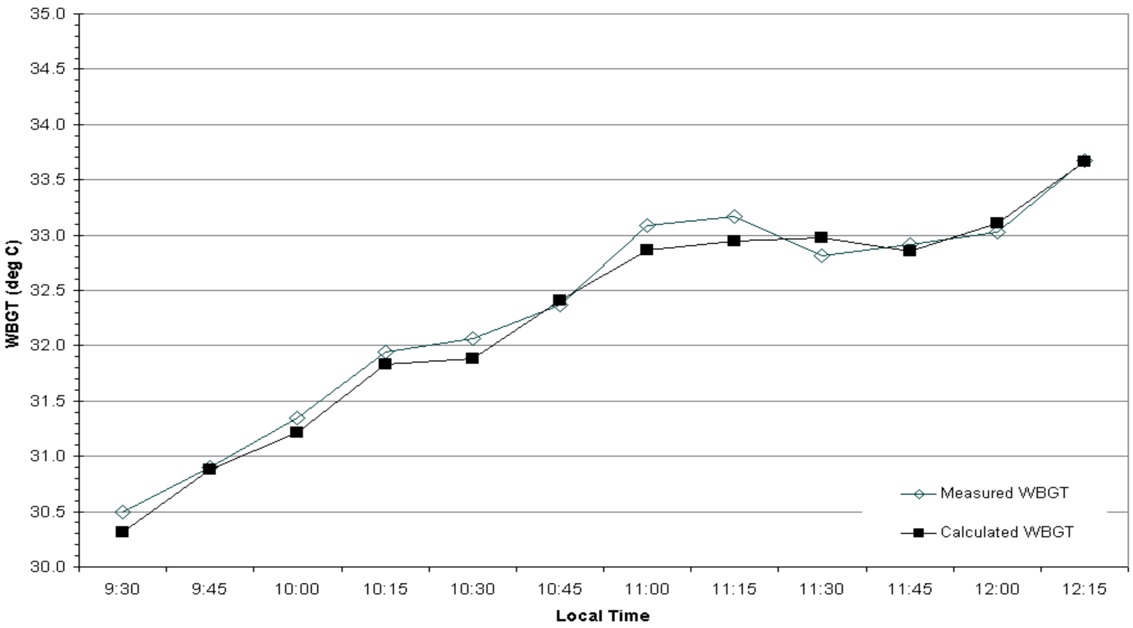
Time constraints following initial development of the WBGT algorithm prevented a full field evaluation; however, a two-phase limited evaluation was conducted prior to operational implementation. First, WBGT estimates were computed using archived meteorological data for a two-month period during the previous heat stress season. The calculated values resulted in a distribution of heat stress categories that were qualitatively consistent with expected summertime conditions, i.e., moderate heat stress conditions were identified on three-fourths of all days during the period and high heat stress conditions were identified on about 20 percent of the days.

Second, calculated values of WBGT were compared to a limited set of co-located field measurements taken at Central Climatology during a 1-week period in early June. Calculated values of WBGT were generally within 2°C of observed values; furthermore, the calculated values were always greater the measured values.

The WBGT data collected during the late spring and early summer of 1999 provided an opportunity to conduct a more rigorous evaluation of the algorithm. Values of WBGT and each of the component temperatures were calculated from 15-minute average data collected at Central Climatology during the nine study days and compared with the corresponding field observations (total of 120 periods). On average, Eq. (3) produced values of T_n that differed from measured values by less than 0.5°C. Similarly, values for T_g from Eq. (4) differed from observed values by an average of 1.5^{o}C (a difference of approximately 3 percent). The difference between observed and calculated T_g was within 2^{o}C ninety-five percent of the time with calculated values generally higher than measured values. Overall, the average difference in observed and calculated WBGT was less than 0.5^{o}C with a maximum difference of 1.3^{o}C.

Figure 2 shows graphically a comparison of calculated WGBT estimates with a set of co-located WBGT observations collected on July 6, 1999. Differences between the observed and calculated values of WBGT were generally less than0.2^{o}C.

Fig. 2. Plot of observed and calculated WBGT (based on Central Climatology data) for July 6, 1999



5. OPERATIONAL IMPLEMENTATION

Based on results from the field evaluations and other operational experience, the WBGT algorithm described above was accepted as a reasonable means of classifying heat stress conditions and accompanying controls on outdoor work. The algorithm was configured to access real-time data from the Central Climatology archived database and automatically execute a calculation at the end of each 15-minute data interval. The output consists of an ASCII file containing the WBGT estimate, the corresponding heat stress class, and other pertinent meteorological data. This file can be easily accessed and viewed by SRS employees through an intranet service. In addition to the real-time WBGT data and heat stress category, the intranet web site contains links to a list of protective controls and other measures for identifying and responding to heat stress symptoms.

6. CONCLUSIONS

A computer algorithm has been developed which calculates reasonable estimates of WBGT using standard meteorological measurements, and disseminates the results in real time via an intranet service. Although manual measurement of WBGT is still appropriate for specific microscale environments, experience over the last three years has shown that the automated algorithm provides an efficient and cost effective means of identifying and communicating the general need for controls on outdoor work.

7. REFERENCES

American Conference of Governmental Industrial Hygienists, *1995-1996 Threshold Limit Values (TLVs) for Chemical Substances and Physical Agents and Biological Exposure Indices (BEIs).*

Budyko, M. I, 1974: Climate and Life, Academic Press, New York, New York.

Houghton, D.D. (editor) and D. M. Driscoll, 1985: *Handbook of Applied Meteorology,* Chapter 29, 778-814, John Wiley & Sons, New York, NY.

Kuehn, L. A., et al, 1970: *Theory of the Globe Thermometer,* Journal of Applied Physiology, Vol. 25, No. 5, 750-757.

Oke, T.R., 1978: *Boundary Layer Climates,* 339-390, Methuen & Co., New York, New York.

Westinghouse Savannah River Company, 1995: *The SRS Heat Stress Management Program*, Procedure Manual 4Q, Procedure 502, Revision 2.