Estimation of Black Globe Temperature for Calculation of the Wet Bulb Globe Temperature Index

Vincent E. Dimiceli, Steven F. Piltz, and Steven A. Amburn

Abstract—**The wet bulb globe temperature (WBGT) index is used in industry, sports and other areas to indicate the heat stress level for humans and animals. One of the values needed to calculate the WBGT Index is the black globe temperature. The black globe temperature is measured using a Black Globe Temperature Sensor which includes a black globe with a thermometer inserted in the center. However, the Black Globe Temperature Sensor can be costly and many of these instruments may be needed to get measurements in many locations. The lead author has derived a formula to estimate the black globe temperature using readily available data collected by the National Weather Service (NWS). The formula was derived from a formula suggested by Kuehn [7], which was based on heat transfer theory. The resulting equation was a fourth degree polynomial in terms of the black globe temperature. It was determined that the black globe temperature can be very accurately approximated by taking a fourth degree polynomial in terms of the black globe temperature to create a linear approximation for black globe temperature. Some preliminary tests indicate accuracy within 0.5˚F.**

Index Terms—**black globe, heat stress, temperature measurement, wet bulb globe temperature**

I. Introduction

One of the government regulations instituted by the Occupational Safety and Health Administration (OSHA) is heat stress management [8]. The manual states in Section III: Chapter 4 the second paragraph of the introduction:

"Outdoor operations conducted in hot weather, such as construction, refining, asbestos removal, and hazardous waste site activities, especially those that require workers to wear semipermeable or impermeable protective clothing, are also likely to cause heat stress among exposed workers."

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A rating is calculated which indicates the safe amount of time a person can work outside on a hot day. This quantity is called the Wet Bulb Globe Temperature Index (WBGT). In the past, WBGT data has been collected manually using a portable instrument. The OSHA manual includes the following formulas for the WBGT:

1. For indoor and outdoor conditions with no solar load, *WBGT* is calculated as:

$$WBGT = 0.7NWB + 0.3GT$$

2. For outdoors with a solar load, WBGT is calculated as

$$WBGT=0.7NWB + 0.2\ \ GT + 0.1DB$$

Where: *GT= globe temperature*

NWB=natural wet-bulb temperature

DB=Dry-bulb temperature

This index is important to the military, sports teams, construction workers, and anyone who will be exerting effort in hot weather. The American Academy of Pediatrics references this index [1] for child safety in hot temperatures. Also, athletes should cancel any outdoor training activity when the WBGT Index is above about 82 degrees Fahrenheit (about 28 degrees Celsius) [2]. The value at which marines will cease all outdoor training activity is about 90 degrees Fahrenheit (about 32 degrees Celsius).

The International Standards (ISO) number 7243 is also based on the WBGT. Parsons [9] gives a good description of how the WBGT Index can be applied globally by considering ISO 7243. One drawback can be the cost of the WBGT device, as well as having personnel trained to use the device.

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Recently the crews that were working on the Gulf oil spill in the summer of 2010 needed this index all along the Gulf Coast. However, in order to collect the data necessary for calculating the WBGT, a relatively expensive device was needed for many different locations along the Gulf coast making this task cost prohibitive. Consequently, the National Weather Service (NWS) was asked to provide the WBGT using only data that is routinely collected by the NWS. The main problem with this is that one of the variables in the equation to calculate the WBGT index is the "globe temperature." This temperature is found by using a copper globe painted in black matte paint with a thermometer inserted so that the bulb is in the center of the globe. This temperature is not routinely collected by the NWS.

Turco, et al. [12] derived equations to estimate the black globe temperature based on meteorological data. However, their model was a statistical model, not a physical model. The equations derived were regression equations computed from meteorological data. Although the equations were extremely accurate, a more accurate model may be derived from the heat equations for the black globe. According to the authors:

"The models developed resulted in great performance to predict the black globe temperature, allowing the estimation of bioclimatic indices to assess the conditions of the environment, to accomplish regional studies, and to indicate best house designs for animals." [12]

This paper shows how the globe temperature can be approximated using only data routinely collected by the NWS. A fourth degree polynomial equation is derived for globe temperature with the coefficients dependent on readily available data. Then, it is shown that the fourth degree polynomial can be reasonably approximated by a linear equation, thus making computation less costly and time-consuming. Finally, some experiments were done to verify the accuracy of the estimate using the linear expression in terms of temperature.

II. Derivation

The following heat equation was taken from a paper by Hunter and Minyard [5], with the exception of the constant (h) in the second term on the right:

$$(1-\alpha_{sps})S\left(f_{db}s_{sp}+(1+\alpha_{es})f_{dif}\right)+(1-\alpha_{spl})\sigma\varepsilon_a T_a^4=\varepsilon\sigma T_g^4+hu^{0.58}(T_g-T_a) \qquad (1)$$

The coefficient in the second term on the right side of equation (h) is from the convective heat transfer coefficient. It was determined during testing that this coefficient varied according to the Solar Irradiance and the cosine of the zenith angle. A multiple power regression was performed to determine an equation for h in terms of S and cos(z), where z is the solar angle to zenith. The equation that approximates h is:

$$h = a(S^b)([\cos(z)]^c) \qquad (2)$$

Where a, b and c are determined experimentally from data using multiple power regression. Now, putting all T_g terms on the left of equation (1), and dividing by $\varepsilon\sigma$ we get:

$$T_g^4+\frac{hu^{0.58}}{\varepsilon\sigma}T_g=\frac{(1-\alpha_{sps})S\left(f_{db}s_{sp}+(1+\alpha_{es})f_{dif}\right)+(1-\alpha_{spl})\sigma\varepsilon_a T_a^4}{\varepsilon\sigma}+\frac{hu^{0.58}}{\varepsilon\sigma}T_a. \qquad (3)$$

The values of all variables except T_g are either given or can be calculated from available data from the NWS. The following values are provided below.

Globe albedo for short and long wave radiation: $\alpha_{sps}=\alpha_{spl}=0.05$ so $1-\alpha_{sps}=1-\alpha_{spl}=0.95$.

Black globe emissivity: ε=0.95

Stephan-Boltzman constant:σ=5.67x10^{-8} is used.

Albedo for grassy surfaces: α_{es}= 0.2.

When these values are entered into equation (3) we get:

$$T_g^4+\frac{hu^{0.58}}{0.95(5.67\times10^{-8})}T_g=\frac{0.95S\left(f_{db}s_{sp}+(1.2)f_{dif}\right)+0.95(\varepsilon_a)\sigma T_a^4}{0.95(5.67\times10^{-8})}+\frac{hu^{0.58}}{0.95(5.67\times10^{-8})}T_a \qquad (4)$$

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Hunter and Minyard, in their paper [5], show that $s_{sp} = \frac{1}{4\cos(z)}$, where z is the solar angle to zenith. Putting this into (4), we get

$$T_g^4 + \frac{hu^{0.58}}{(5.3865x10^{-8})}T_g = S\left(\frac{f_{db}}{4\sigma\cos(z)} + \frac{(1.2)}{\sigma}f_{dif}\right) + \varepsilon_a T_a^4 + \frac{hu^{0.58}}{0.95\sigma}T_a \quad (5)$$

Where S is solar irradiance, f_{db} is the direct beam radiation from the sun and f_{dif} is the diffuse radiation from the sun. The Stefan-Boltzman Constant is σ and *h* is the convective heat transfer coefficient. The convective heat transfer coefficient is calculated experimentally as indicated above. Finally, the ambient temperature is represented by T_a and the wind speed by u in meters per hour. All of these are given or may be calculated directly from data given by the NWS.

The last parameter on which the globe temperature depends is the thermal emissivity, ε_a. According to Hunter and Minyard [5], thermal emissivity can be calculated using

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

Where e_a is atmospheric vapor pressure, which may be calculated by

$$e_a = \exp\left(\frac{17.67(T_d - T_a)}{T_d + 243.5}\right) \times (1.0007 + 0.00000346P) \times 6.112\exp\left(\frac{17.502T_a}{240.97 + T_a}\right) \quad (7)$$

where P is the barometric pressure and T_d is the dew point temperature.

When we take into consideration the fact that all parameter values in equation (5) are constants that can be entered at constant time intervals, we can reduce the equation to

$$T_g^4 + CT_g = B + CT_a \ , \quad (8)$$

Where

$$C = \frac{hu^{0.58}}{(5.3865\times10^{-8})} \quad \text{and}$$

$$B = S\left(\frac{f_{db}}{4\sigma\cos(z)} + \left(\frac{1.2}{\sigma}\right)f_{dif}\right) + (\varepsilon_a)T_a^4.$$

By doing this, we can treat (8) as a fourth degree polynomial in terms of T_g. The values of T_g in which we are interested are in the interval [20, 60], since values below 20˚C are too cold to cause heat stress and values above 60˚C, in general, do not occur. Figure 1 shows a graph of $y = t^4 + Ct$ and y1=Ct – 7,680,000 (the tangent line approximation for the function y at t=40) on the interval [20, 60] (*C* was calculated for a wind speed of about 15 mph).

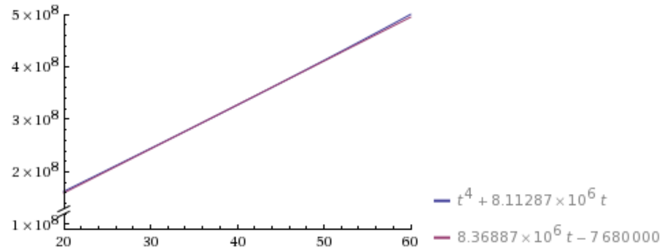

Figure 1. The graph of $y = t^4 + Ct$ and y1=Ct – 7,680,000 for C≈8,389,000 and t between 20 and 60.

Notice that the curve appears to be very close to the linear graph. We compute the curvature for y to see how close to a linear function y is. The curvature of $y = t^4 + Ct$ is given by

$$k = \frac{12t^2}{(3t^3 + C)^{(3/2)}} \quad (9)$$

In order to get an understanding of the magnitude of the curvature, consider the graph (Figure 2) of the function $k(t,u) = \frac{12t^2}{(3t^3 + C(u))^{(3/2)}}$ for u between 1 mph and 40 mph (1690 meters per hour to about 65,000 meters per hour) and t between 20˚C and 60˚C.

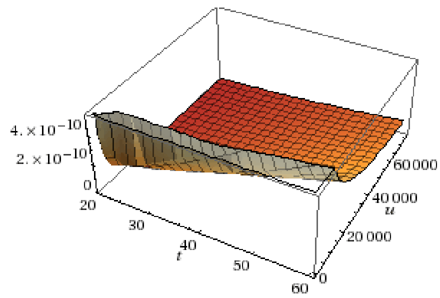

Figure 2. Pictured above is the curvature of y for 20<t≤60 and 1≤u≤76,000.

Notice that the curvature is on the order of 4×10^{-10} or less on the domain of interest. This confirms the assumption that y is nearly linear for values of t and u that make sense for this context. It is therefore reasonable to use a linear approximation for y to solve for t (=T_g). In other

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words we may use a linear approximation on the left side of equation (8) to estimate the value of the globe temperature.

Using differential calculus to find the equation of the tangent to the curve at t=40 (the midpoint of the interval [20, 60]), we find that the left side of equation (8) may be substituted by

$$y_{est} = CT_g + 256000T_g - 7680000. \quad (10)$$

Putting this in place of the left side of equation (8) and solving for T_g, we get

$$T_g = \frac{B + CT_a + 7680000}{C + 256000} \quad (11)$$

with B, C and T_a as defined previously. Now we have an estimate of Tg dependent only on values which are either readily available from the NWS or may easily be calculated from data available from the NWS. Also, the equation is linear making for easier computation than what was necessary to solve the original fourth degree polynomial.

III. Preliminary Tests

In September, 2010, three preliminary tests were conducted to test the accuracy of the globe temperature estimate. A Black Globe Temperature Sensor for heat stress was created by an employee of the NWS using specifications from an article by Purswell and Davis [7]. A picture of the unit is included in Figure 3. This unit was used to get some preliminary readings to check for accuracy of the equation.

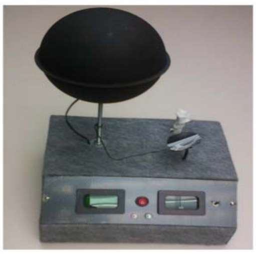

Figure 3. Black Globe Temperature Sensor used in preliminary tests.

Figure 4. Black Globe Temperature Sensor for Heat Stress used to verify equations at the Oklahoma Mesonet test facility in Norman Oklahoma.

The first preliminary test was done on September 9, 2010 in front of the NOAA offices in Tulsa, Oklahoma. The weather conditions were hazy that day with air temperature 86˚F, and dew point temperature 69˚F. The barometric pressure was 30.08 in. of Hg (about 993 mb for pressure not adjusted for sea level) and the solar irradiance was 336 W/m^2. The wind speed averaged around 5 to 6 mph during the measurement. The globe temperature was measured to be 91˚F using a black globe as described earlier in this paper. Using Excel, a spread sheet was created to use the derived equation to estimate globe temperature. The equation estimated the globe temperature to be about 91.434˚F.

Another preliminary test was performed on September 10, 2010. The conditions were sunny with air temperature 93˚F and dew point temperature 76˚F. The barometric pressure was 29.75 in. of Hg (about 982 mb for pressure not adjusted for sea level) and the solar irradiance was 754 W/m^2. The wind speed was measured at about 7 mph during the measurement. The globe temperature was measured to be 103˚F using a black globe. The equation estimated the globe temperature to be about 102.757˚F.

The third preliminary test was performed on September 17, 2010. The conditions were similar to the conditions on September 10. The air temperature was 94˚F and dew point temperature 76˚F. The barometric pressure was 30.05 in. of Hg (about 992 mb for pressure not adjusted for sea level) and the solar irradiance was 579 W/m^2. The wind speed was measured at about 3.7 mph during the measurement. The globe temperature was measured to be 105˚F using a black globe. The equation estimated the globe temperature to be about 105.175˚F.

The three preliminary tests indicate that the formula used to estimate the globe temperature is very accurate. If the estimate is within 1˚F, it is sufficient to estimate the WBGT index. As can be seen from the preliminary tests, the estimates are within about 0.5˚F. The main problem with our tests was that we had to estimate the wind speed and the formula is very sensitive to the value of the wind speed. However, the estimates for wind speed should be within about 0.5-1 mph. Also, these tests were all done at about the same time of day. Therefore, the solar irradiance and the cosine

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of the zenith angle were about the same for all preliminary tests.

IV. Tests with official WBGT Sensor

An official black globe was set up at the Oklahoma Climatological Survey site in Norman Oklahoma for data collection in June, 2011. The data from this site was then analyzed to determine accuracy of the black globe temperature equation. After extensive analysis and the derivation of the Multiple Power Regression Equation for the heat transfer coefficient, h, equation (11) was successful in calculating the black globe temperature to within one degree Celsius. An Excel document has been included in the appendix indicating the accuracy of the equations for different times of the day on two days in July.

The instrument was set to collect data every minute. The data collected included the black globe temperature, natural wet bulb temperature, ambient temperature, and relative humidity. Wind speed at 2 meters above ground, solar irradiance, and barometric pressure were collected, as well. The data was then retrieved via the internet.

As can be seen from the Excel document in the appendix, the black globe temperature was estimated to within 0.666° C in every case. Since the factor for the black globe temperature in the WBGT Index equation is 0.2, this error will contribute less than 0.15° C to the WBGT Index error.

V. An Algorithm

In this section, an algorithm is created for the calculation of globe temperature estimates. First, we will consider the values readily available from the NWS. These will be input values to be entered at the beginning of the program.

1. The values to be entered are wind speed (u in meters per hour), ambient temperature (T_a in degrees Celsius), dew point temperature (T_d in degrees Celsius), solar irradiance (S in Watts per meter squared), direct beam radiation from the sun (f_{db}) and diffuse radiation from the sun (f_{dif}).
2. The zenith (z) angle may be entered or calculated. (The angle, z, must be in radians for Excel.)
3. The thermal emissivity must be calculated next. Using the following two equations.

a. $e_a = \exp\left(\frac{17.67(T_d - T_a)}{T_d + 243.5}\right) \times (1.0007 + 0.00000346P) \times 6.112\exp\left(\frac{17.502T_a}{240.97 + T_a}\right)$

b. $\varepsilon_a = 0.575e_a^{(1/7)}$

4. Now B and C can be calculated using the following equations.

a. $B = S\left(\frac{f_{db}}{4\sigma\cos(z)} + \frac{(1.2)}{\sigma} f_{dif}\right) + (\varepsilon_a)T_a^4$

b. $C = \frac{hu^{0.58}}{5.3865x10^{-8}}$, where h is computed using (2).

5. Finally the estimate for globe temperature is calculated using equation (10).

$$T_g = \frac{B + CT_a + 7680000}{C + 256000}$$

VI. National Weather Service Applications

The National Weather Service produces forecasts and observations of numerous meteorological parameters. One of these is the apparent temperature or Heat Index, based on work by R.G. Steadman [11]. In this work, Steadman constructed a table which uses relative humidity and dry bulb temperature to produce the "apparent temperature" or the temperature the body "feels." The OSHA uses a more detailed approach based on the WBGT Index [8] which provides guidelines to protect workers. In an effort to provide decision makers with forecast information on the WBGT, the National Weather Service in Tulsa has implemented and is testing the algorithm described earlier in this paper.

The algorithm is being tested for feasibility and accuracy in the forecast and also the hourly analysis of WBGT. In the current test phase, the first goal is to provide real-time, hourly estimates of WBGT across the WFO Tulsa forecast area of eastern Oklahoma and northwest Arkansas. The second goal is to make forecasts of WBGT out seven days to provide decision makers with important planning information. Ultimately, the algorithm will be offered to all National Weather

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Service Offices across the United States and elsewhere.

The National Weather Service uses a forecast system called the Graphical Forecast Editor, or simply GFE [6]. Virtually all weather variables are included in the system in a gridded format at either 2.5 km resolution or 5 km resolution. Grid fields of forecast parameters such as air temperature, dew point temperature, wind, pressure, cloud amount, the probability of rain, rainfall amounts, and many others are produced through a forecast period of seven days. From these parameters, an assortment of secondary forecast variables can be created through various algorithms. Some of these currently include relative humidity, wind chill index, heat index, icing index, wild fire spread index, and others. The WBGT algorithm described here will be tested and eventually added to the suite of products issued by WFO Tulsa.

An example of the WBGT Index graphics page is shown in Figure 4. This indicates the variability of the index across the forecast area due to differences in the contributing parameters. The darker areas indicate higher index values. Graphical forecasts of the WBGT may eventually be available to the public and decision makers, along with point forecasts of WBGT for any location on the map.

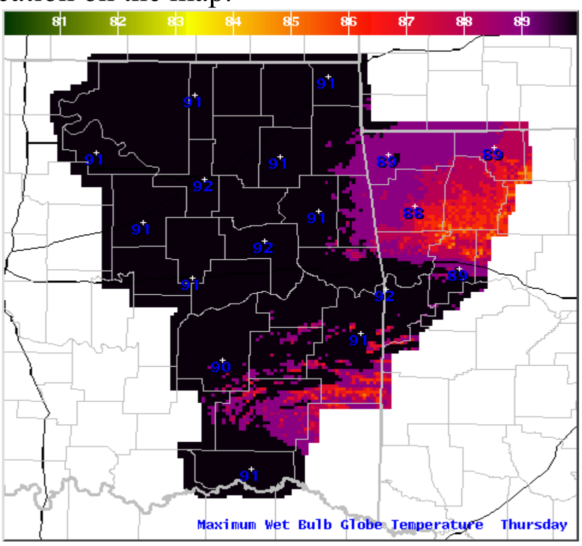

Figure 5. Display of WBGT index from WFO Tulsa Graphical Forecast Editor

VII. CONCLUSION

The black globe temperature, until now, has either been measured using a Black Globe Temperature Sensor on site, or by using a regression equation to estimate the WBGT. One example of this equation is used by the Australian Bureau of Meteorology, but “does not take into account variations in the intensity of solar radiation or of wind speed” [4]. Dimiceli has derived a linear expression to estimate the black globe temperature to within about 0.666 ˚C, thus estimating the WBGT Index to within about 0.333 ˚C or .733 ˚F. More tests have been performed using an official Black Globe Temperature Sensor. These tests provided data to get a multiple power regression equation to estimate the convective heat transfer coefficient (*h*) used in the estimation of the black globe temperature in the formula (11) by Dimiceli.

The formula has been added to an internal experimental web page in order to allow computation of the WBGT Index for a limited area. This web page allows interested parties to calculate the WBGT Index for their local area by entering the ambient temperature (T_a) and approximate average wind speed at their location. A tool which will be available to anyone interested in computing the danger of heat stress at their particular location is being created at the writing of this article. By doing this, the NWS will give sports teams, construction companies, military personnel, and other affected people, the ability to determine the danger of working in the heat at different times of the day. Eventually an application for cell phones will be designed to calculate the WBGT Index. It is the investigators’ hope that this index will eventually be used nationally (or even internationally as Parsons [9] proposed in his article) by the NWS to indicate the dangers of heat stress in any location in the country.

APPENDIX

Table 1: Preliminary Tests

	9/9/2010		9/10/2010		9/17/2010	
fdb	0.67		0.75		0.75	
fdif	0.33		0.25		0.25	
Ta ˚F ˚C	86	30	93	33.889	94	34.444
Td ˚F ˚C	69	20.556	76	24.444	70	21.111
P in. of merc, mb	30.08	992.83	29.75	981.94	30.05	991.84
S W/m^2	0.336	336	0.754	754	0.579	579
z degrees radians	38.44	0.6709	36.65	0.6397	41.41	0.7227
u mph, mtrs per hr	6	9654	7	11263	3.7	5953.3
Rh	67.5		54.27		52	
Tw ˚C	26.7755045		26.5755611		26.34526836	
ea	22.6486791		28.4870860		22.48619082	
epsa	0.89793603		0.92784344		0.897012895	
B	3614652151		7098450550		5617678219	
C	1197110170		1309071170		904405917.3	
Tg ˚C ˚F	33.0188360	91.434	39.3095775	102.76	40.65288578	105.18
e	28.543833		28.5844209		28.24707268	
actual Tg ˚F ˚C	91	32.778	103	39.444	105	40.556
WBGT						
dimiceli	28.3466203	83.024	29.8536972	85.737	30.01670945	86.03
actual	28.2984087	82.937	29.8806707	85.785	29.99724341	85.995
australia	32.1677267	89.902	34.3886774	93.9	34.57109956	94.228

The table above is the Excel Document which shows the results of the three preliminary tests run in September.

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Table 2. Some results from official Black Globe Sensor

	12:30	7/3/2010	13:00	7/3/2010	14:00
fdb		0.75		0.75	
fdif		0.25		0.25	
Ta (˚C)		26.26		28.8	
Td (˚C)		17.21		17.57	
P mb		973.62		973.71	
S W/m^2		193.04		448.7	
cos(z)		0.9714		0.9244	
u (m per sec, m per hr)	6487.2	1.812	6523.2	2.164	7790.4
Rh		57.5		50.7	
h		0.101274459		0.132569543	
Tw (˚C)		20.94781261		21.45412447	
ea		18.55668613		18.59184046	
epsa		0.872734593		0.872970592	
B		1678945078		3979819932	
C		306605873.4		444878843.2	
Tg (˚C ˚F)	88.98574	31.73445826	89.122	37.74139651	99.9345
e		19.56661611		20.00916235	
actual Tg ˚F ˚C		31.55		37.16	
error		-0.18445826		-0.58139651	

	15:30	7/10/2010	13:00	7/10/2010	14:00
fdb	(not avgd)	0.75		0.75	
fdif		0.25		0.25	
Ta (˚C)		29.5		31.06	
Td (˚C)		16.2		16.59	
P mb		971.03		971.37	
S W/m^2		173		387.98	
cos(z)		0.9689		0.9226	
u (m per sec, m per hr)	13500	2.734	9842.4	3.86	13896
Rh		44.65		41.86	
h		0.098524678		0.127660528	
Tw (˚C)		20.46198409		20.86084154	
ea		16.74872176		16.93891306	
epsa		0.860047363		0.86143581	
B		1506448296		3444243993	
C		378649115.5		599274858.9	
Tg (˚C ˚F)	109.0913	33.47613079	92.257	36.80444598	98.248
e		18.34712008		18.80503063	
actual Tg ˚F ˚C		33.58		37.47	
error		0.103869211		0.665554019	

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