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ASSESSMENT OF THE RELIABILITY OF A CORRECTION PROCEDURE FOR WGT (BOTSBALL) MEASUREMENTS OF HEAT STRESS

U S ARMY RESEARCH INSTITUTE

OF

ENVIRONMENTAL MEDICINE

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Matthew, W., Thomas, G., Armstrong, L., and R. Hubbard

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The Botsball or WGT (Wet Globe Thermometer) has been widely distributed to military users as a rugged, simple, and inexpensive alternative to WBGT (Wet Bulb-Globe Temperature) instruments. Existing hot weather guidelines for the Botsball presumed that the Botsball would always read approximately $2°F$ ($1.6°C$) lower than the prevailing WBGT index. Following reports from the field of Botsball readings as much as $10°F$ ($5.6°C$) lower than the prevailing WBGT index during hot, dry, and windy conditions, a wind tunnel study was conducted to assess Botsball performance characteristics over a broad range of temperatures, humidities, and wind speeds (USARIEM Technical Report No. T9/86). The wind tunnel study confirmed that substantial and potentially dangerous underestimates of heat stress on the order of $11°F$ ($6.1°C$) may be obtained with the Botsball under very hot, dry, and windy conditions. In an effort to derive a practical correction process that would, with reasonable precision, correct the Botsball reading to parity with the prevailing WBGT index, the wind tunnel data were reexamined. A mathematical relationship incorporating (continued)

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one additional measurement, DB (Dry Bulb) was found to provide an average bias ($\overline{D}$) of -0.1°F (0.06°C) with a variation (± 2 Standard Deviations) of ±1.6°F (0.9°C) around that bias. The equation, derived from the wind tunnel study, was: WBGT = 0.8 X Botsball Reading + 0.2 X DB + 1.3°F (0.7°C). The present study was conducted to determine the reliability of the correction procedure in natural heat stress environments. Performance of the correction procedure was assessed in both desert and jungle environments in Australia in February 1987. Using the correction equation and a DB measurement obtained from the dial thermometer component of the Botsball itself, overall bias ($\overline{D}$) was found to be +2.6°F (1.4°C) and the precision estimate (±2SD) was ±2.9°F (1.6°C). Although the procedure therefore generally overestimates the WBGT index, it does appear to provide a conservative safety margin that would permit continued use of the Botsball under any heat stress condition.

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TECHNICAL REPORT

No. 17/87

ASSESSMENT OF THE RELIABILITY OF A CORRECTION
PROCEDURE FOR WGT (BOTSBALL) MEASUREMENTS
OF HEAT STRESS

by

William T. Matthew, Glenn J. Thomas,

Lawrence E. Armstrong, Ph.D, and

Roger W. Hubbard, Ph.D

Project Reference: 3E162777A879

US ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts 01760-5007

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I. INTRODUCTION

Effective implementation of existing military hot weather doctrine requires accurate measurement of environmental heat stress. The WBGT (Wet Bulb Globe Temperature) index has remained the standard measure of heat stress used in both industrial and military applications (1,2). The WGT (Wet Globe Thermometer) also known as the Botsball (NSN 6665-01-103-8547), was recently introduced as a lightweight, rugged, and inexpensive alternative to the cumbersome standard WBGT apparatus described in TB MED 507. Based on its reported close correlation with the WBGT index, the WGT has been used as a measurement device for implementing hot weather guidance on optimal work/rest cycles and hourly water consumption requirements (3). The stated relationship (3) is: WGT = WBGT - 2^{O}F $(1.1^{O}$C). The WGT has been widely distributed and used by US forces in Europe, Central America, and the Middle East as well as at training sites throughout the United States.

In 1983, reports of Botsball readings as much as 10°F $(5.6^{O}$C) lower than the prevailing WBGT index were received from two different locations: Fort Bliss, Texas and the Sinai, Egypt. In response to those reports, a wind tunnel study was conducted to assess Botsball performance characteristics over a broad range of temperatures, humidities, and wind speeds (4). The results of that study confirmed that the Botsball underestimates heat stress by as much as 11°F $(6.1^{O}$C) under extremely hot, dry, and windy conditions. It was concluded that the assumed 2^{O}F $(1.1^{O}$C) offset for WGT readings would be totally inadequate and potentially dangerous if applied in very hot/dry desert environments.

Following publication of the wind tunnel study report, the data were re-examined in an effort to derive a 'correction' equation that would, with reasonable precision, correct the Botsball reading to parity with the prevailing WBGT index. A relationship, incorporating one additional measurement, DB (Dry Bulb), was found to provide an average bias ($\overline{D}$) of -0.1^{O}F $(0.06^{O}$C) with a variation ($\pm$2 Standard Deviations) of $\pm$ 1.6^{O}F $(0.9^{O}$C) around that bias. The equation, derived from the wind tunnel data is:
  WBGT = 0.8 X Botsball reading + 0.2 X DB + 1.3^{O}F $(0.7^{O}$C)

While these results suggested that it might be possible to obtain accurate heat stress measurements using the Botsball and this equation, two major issues would have to be resolved before the procedure could be implemented with confidence in field situations:

a. Accuracy: The correction equation was derived from wind tunnel environments which are at best limited simulations of natural environments. In the wind tunnel tests, the solar radiation component was simulated with incandescent lamps and the intensity was held constant at 800 Watts.m^{-2}. In a natural heat stress environment, the solar radiation could vary from 0 to 1150 Watts.m^{-2} during the course of a day and would have significant potential to degrade the fairly accurate performance of the correction procedure seen with the wind tunnel data. It was therefore necessary to document the accuracy of the correction procedure in natural, dynamic heat stress environments.

b. Technical Feasibility: In the re-analysis of the data from the wind tunnel study, the DB (Dry Bulb, air temperature) measurement was taken from a seperate air temperature sensor located in the wind tunnel. In the field, DB would have to be measured using the dial thermometer component of the Botsball itself. It was therefore necessary to document, in natural heat stress environments, the effects of mechanical strain on the Botsball thermometer from repeated removal, the ability to adequately shade the sensor tip from direct sunlight during the DB measurement, and the adequacy of the dial themometer's upper limit of 120°F (49°C).

In recognition of these issues, a tasker was received from OTSG (5) through MRDC (6) for USARIEM to formally validate the correction procedure under field conditions.

II. OBJECTIVE

The objective of this effort was to document, under field conditions, the accuracy and technical feasibility of a Botsball correction procedure employing the Botsball reading, a DB (air temperature) measurement made with the Botsball's dial thermometer, and the correction equation derived from the wind tunnel data.

III. SCOPE OF EFFORT

1. The scope of this effort was limited to heat stress environments out of doors and did not include crew compartment assessments.

2. The data collection effort was focused on two climate types only: hot-dry desert and hot-wet jungle. Site selection and data collection schedules were further focused to obtain, for each climate type, heat stress conditions in the WBGT index region between 78°F (26°C) and 90°F (32.2°C) which has special relevance to existing guidelines.

Although the problem of underestimated heat stress with the Botsball appeared to be associated with hot-dry desert conditions, it was important that potential users be able to apply the correction procedure consistently, without having to make any subjective judgement about whether the environment was hot-dry or hot-wet.

3. This effort focused on evaluating the accuracy and technical feasibility aspects of the proposed Botsball correction procedure and did not address 'ease of use' issues that might affect operational implementation. Those issues will be addressed in seperate user level field evaluations to be conducted by HSC and FORSCOM personnel in early summer 1987 (5).

IV. MEASUREMENTS

1. WBGT Instruments:

The WBGT index served as the measurement standard for evaluating the performance of the Botsball correction procedure. The apparatus consisted of a naturally convected wet bulb, shaded dry bulb, and 6 inch (15 cm) Vernon black globe. Each of these components was instrumented with an electronic temperature sensor probe (400 series thermistors, Yellow Springs Instrument Co.) and a battery operated digital readout thermometer (model 8110, Cole-Parmer, Inc.). The WBGT index was computed from the temperature of the individual components as follows:

WBGT = 0.1 x dry bulb + 0.7 x wet bulb + 0.2 x black globe

In order to provide ancillary data on the performance of potential alternatives to the full size WBGT apparatus described above, additional WBGT data were collected using two instruments currently available through the military supply system: the mechanical Stortz WBGT Kit (NSN 6665-00-159-2218), and the electronic Reuter-Stokes NAVSEA meter (NSN 6685-01-159-5298).

2. Botsballs:

Botsballs (NSN 6665-01-103-8547), Howard Manufacturing Co., were obtained through military supply channels. Readings from three Botsballs were recorded at each measurement time.

3. Additional Instrumentation:

A battery operated portable weather station (MET SET 4B, MET ONE, Inc.) provided a continuous record of wind speed and direction, shaded dry bulb temperature, solar radiation

levels, and relative humidity. A sling psychrometer was also used to obtain manual relative humidity readings at each measurement time.

4. Instrumentation Deployment Considerations:

    a. All measurements were made at a height of 4 ft (1.2 m) above ground level.

    b. Desert test site afforded full sun exposure during the daylight hours, and unobstructed wind flow to the test instruments.

    c. Jungle test site was selected to provide full sun exposure. Limited measurements under jungle canopy were obtained.

    d. Ground surfaces at test sites, desert and jungle, were natural, "unimproved" surfaces representative of those climate types (sand, grass, and forest floor).

5. Measurement Cycles:

    Measurements were made at half hour intervals between sunrise and sunset. It was anticipated that the natural diurnal variation in environmental parameters would afford a sufficiently broad range in values for each climate type to provide a practical level of statistical reliability after 2-3 full days of data collection.

6. Calibration of Temperature Measuring Devices:

    Calibration checks on the Botsball dial thermometers and the electronic digital thermometers used to instrument the standard WBGT apparatus were performed using a Hewlett Packard model 2804 Quartz Thermometer having a NBS traceable accuracy better than $\pm$ 0.1°F (0.06°C). The three Botsball dial thermometers all read within 0.5°F (0.3°C) of the Quartz Thermometer. Since this was better than the 1.0°F (0.6°C) accuracy specified by the manufacturer, the dial thermometers were not readjusted. Readings obtained during the field test therefore reflect inter-instrument variability that is typical of new Botsballs in 'as is' states of calibration. The three electronic digital thermometers used to instrument the dry bulb, wet bulb, and black globe components of the standard WBGT apparatus all read within 0.1°F (0.06°C) of the Quartz Thermometer.
    Calibration checks were performed in our laboratory prior to departure and again upon our return. There was no significant deterioration of the accuracy of these instruments over the test period.

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7. Botsball Measurement Procedure:

Readings from three Botsballs, located approximately 12 inches (.3 m) apart at identical heights, were obtained at each measurement cycle. The procedure was as follows:

1. Fill Botsball reservoir with water 10 minutes prior to read time. Botsball wicks were never allowed to dry out between measurement cycles.

2. At measurement time, record Botsball readings to nearest 0.25 $^{\circ}$F.

3. Immediately remove dial thermometers from Botsballs and shade the metal tip and stem from direct sunlight with readers shadow, holding the thermometer 8 to 10 inches away from the body. After 3 minutes, record the reading on the dial thermometer to the nearest 0.25°F. This is the shaded dry bulb temperature, DB.

4. Re-insert the dial thermometers into the Botsballs.

5. Compute the predicted WBGT index using the equation: WBGT = 0.8 x Botsball reading + 0.2 x DB + 1.3 $^{\circ}$F (0.7°C)

V. TEST LOCATIONS/ENVIRONMENTAL CONDITIONS

With the kind invitation of the Royal Australian Army Medical Corps (RAAMC) we were afforded the opportunity to conduct this test in Australia, in February, 1987. Since peak temperatures of the Australian summer occur in February, and since both desert and jungle climate types are found there, this represented an opportunity to accomplish the test objective efficiently and in advance of the 1987 heat stress season in the Northern Hemisphere.

Royal Australian Army Medical Corps personnel provided us with access to the Joint Tropical Trials and Research Establishment facilities near Innisfail in Queensland for the jungle testing and they coordinated the necessary approvals for desert testing at Yulara Township, Ayers Rock, Northern Territory. Characteristics of each location are described below:

1. JUNGLE - Joint Tropical Trials and Research Establishment (JTTRE).

a. The Jungle test site was located at the JTTRE installation at Cowley Beach in Innisfail, Queensland, Australia. The Cowley Beach area is comprised of 10,131

acres (4100 ha) of coastal lowland plain and includes
secondary rainforest, 4.8 miles (8 km) of beach, savannah,
swamp, sand, and mangroves. Our test site was approximately
[5~.5 miles (.8 km) inland in a 50 ft x 50 ft (15.1 m x 15.1
m) clearing in secondary rainforest. Equipment set-up was
accomplished with minimal damage to natural low level ground
cover. Data for this test site were collected on two
consecutive days from approximately 0700 hrs to 1930 hrs.
Data collected under the jungle canopy was taken in an area
of dense vegetation approximately 25 yards (22.8 m) from the
clearing.

   b. Ranges for environmental parameters measured at this
site were as follows:

Dry bulb °F (°C)	76.0 - 94.5	(24.4 - 34.7)
Wet bulb °F (°C)	75.1 - 82.6	(23.9 - 28.1)
Black Globe °F (°C)	77.0 - 126.5	(25.0 - 52.5)
WBGT °F (°C)	75.6 - 92.7	(24.2 - 33.7)
Wind Speed MPH (KPH)	0.5 - 3.0	(0.3 - 1.9)
Solar Radiation W.m^{-2}	66.0 - 1066.0	
% Relative Humidity	54.7 - 93.3	

2. DESERT - Ayers Rock.

   a.   The Desert test site was located within the
boundaries of the Yulara township, Ayers Rock, Northern
Territory, Australia. Our test site was in a vegetated
desert characterized by low relief (< 5m) and gently rolling
terrain. Equipment set-up was accomplished with minimal
damage to natural low level ground cover. Data for this
test site were collected for 3 consecutive days from
approximately 0700 hrs to 1930 hrs.

   b. Ranges for environmental parameters measured at this
site were as follows:

Dry bulb °F (°C)	64.0 - 109.2	(17.8 - 42.9)
Wet bulb °F (°C)	51.6 - 68.4	(10.9 - 20.2)
Black Globe °F (°C)	69.4 - 135.3	(20.8 - 57.4)
WBGT °F (°C)	56.4 - 85.5	(13.6 - 29.7)
Wind Speed MPH (KPH)	2.0 - 12.0	(1.2 - 7.5)
Solar Radiation W.m^{-2}	99.8 - 1133.0	
% Relative Humidity	15.8 - 48.6	

VI. ACCURACY ASSESSMENTS FOR THE PROCEDURE

   1. The data analysis approach was based on the concept
that accuracy has two components:

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a. Average error or bias is the average difference between the 'observed' value and the 'true' value. It represents systematic error. In our analyses, this component was computed as the D statistic, where the 'corrected' Botsball reading was the 'observed' value and the reading from the standard WBGT apparatus was the 'true' value.

b. Precision is a measurement of variability. It represents random error. In our analyses, this component was computed as the Standard Deviation (SD) of the D statistic. Since $\pm$ 1 SD includes only 66% of normally distributed variation, it was felt that $\pm$ 2 SD, which includes 95% of normally distributed variation, would be more appropriate for evaluating the precision bandwidth of the Botsball 'correction' procedure.

VII. RESULTS

1. Accuracy:

Performance of the correction procedure is depicted graphically in Figure 1. Points falling exactly on the diagonal line (line of identity) are perfect corrections, those falling above it are too high and those falling below it are too low. The parallelogram shape superimposed on the diagonal line is $\pm$ $2^{\circ}F$ $(1.1^{\circ}C)$ over the important doctrine range of 78 to $90^{\circ}F$ (26 to $32.2^{\circ}C$). Clearly most of the corrections were too high, the procedure was over-correcting the Botsball. The average error, or bias, was + $2.6^{\circ}F$ $(1.4^{\circ}C)$ for the combined jungle and desert Botsball corrections.

Precision (assessed as $\pm$ 2 Standard Deviations of D) was found to be $\pm2.9^{\circ}F$ $(1.6^{\circ}C)$. From these values for average error and precision, accuracy limits for 95% of Botsball corrections defined a band which extends from $0.3^{\circ}F$ $(0.2^{\circ}C)$ below to $5.5^{\circ}F$ $(3.1^{\circ}C)$ above the prevailing standard WBGT index.
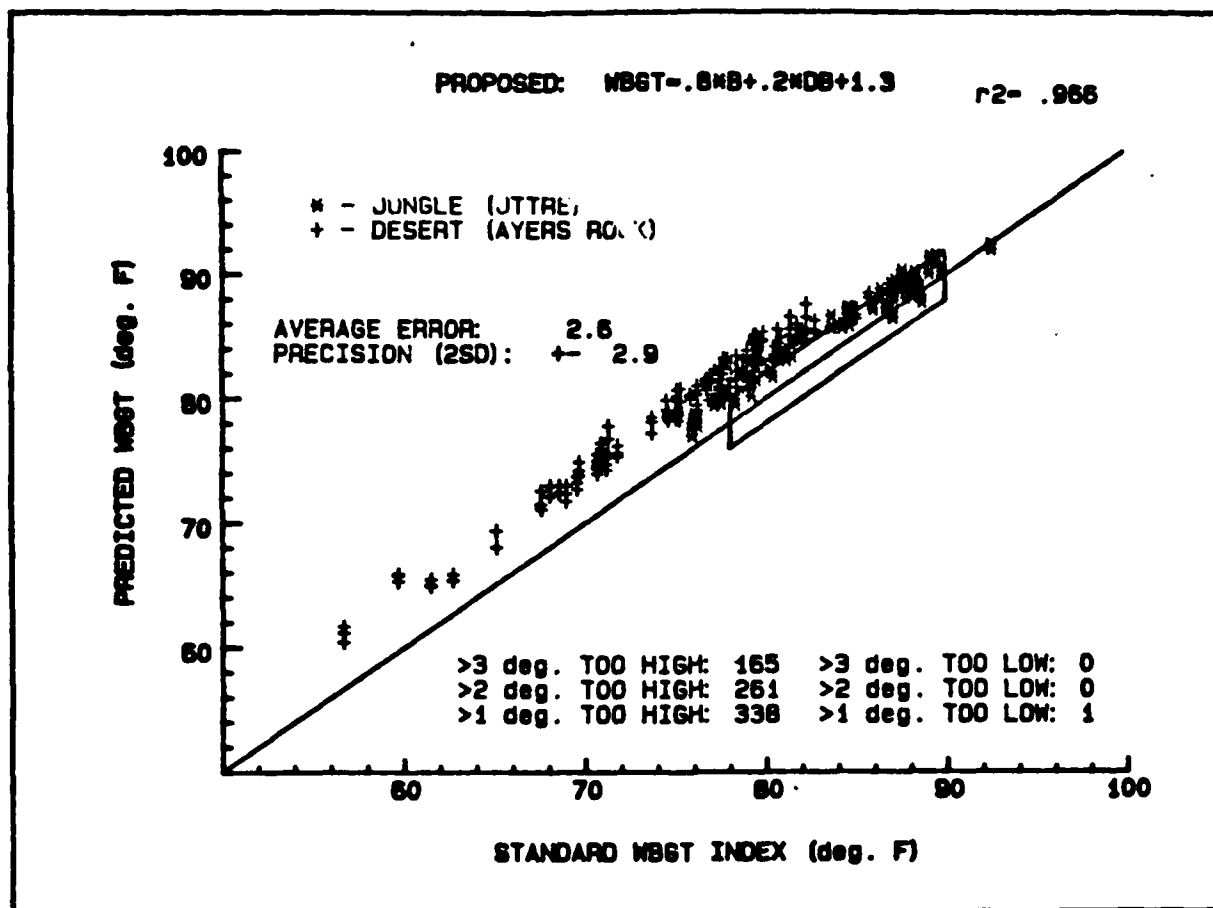
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Fig. 1 Accuracy of Proposed Correction Procedure relative to Standard WBGT Apparatus.

This represents a serious deterioration of the overall accuracy seen with the wind tunnel data where the accuracy band extended from $1.7^\circ F$ ($0.9^\circ C$) below to $1.5^\circ F$ ($0.8^\circ C$) above the prevailing standard WBGT index.

2. Technical Feasibility:

The feasibility of obtaining an accurate DB (dry bulb) measurement using the dial thermometer component of the Botsball was confirmed in these tests. Using the shaded dry bulb component of the standard WBGT apparatus as the true DB, the DB obtained from the Botsball's dial thermometer was found to have an average error of $-0.4^\circ F$ ($0.2^\circ C$) and a precision estimate of $\pm 3.8^\circ F$ ($2.1^\circ C$). Since the DB is weighted at 20% in the Botsball correction equation, its average error contribution to the corrected Botsball value reduces to $-0.1^\circ F$ ($0.05^\circ C$) and its contribution to correction precision reduces to $\pm 0.8^\circ F$ ($0.4^\circ C$).

3. Alternative WBGT Instrumentation

Performance of the Stortz WBGT Kit and the Reuter-Stokes NAVSEA Meter relative to the standard WBGT apparatus are shown in figures 2 and 3. Although the performance of the Reuter-Stokes NAVSEA Meter was consistent with results obtained in the wind tunnel study, the Stortz WBGT Kit showed considerable increase in both the average error and precision estimates. The precision band for the Stortz WBGT Kit was in fact worse than for the corrected Botsball reading.
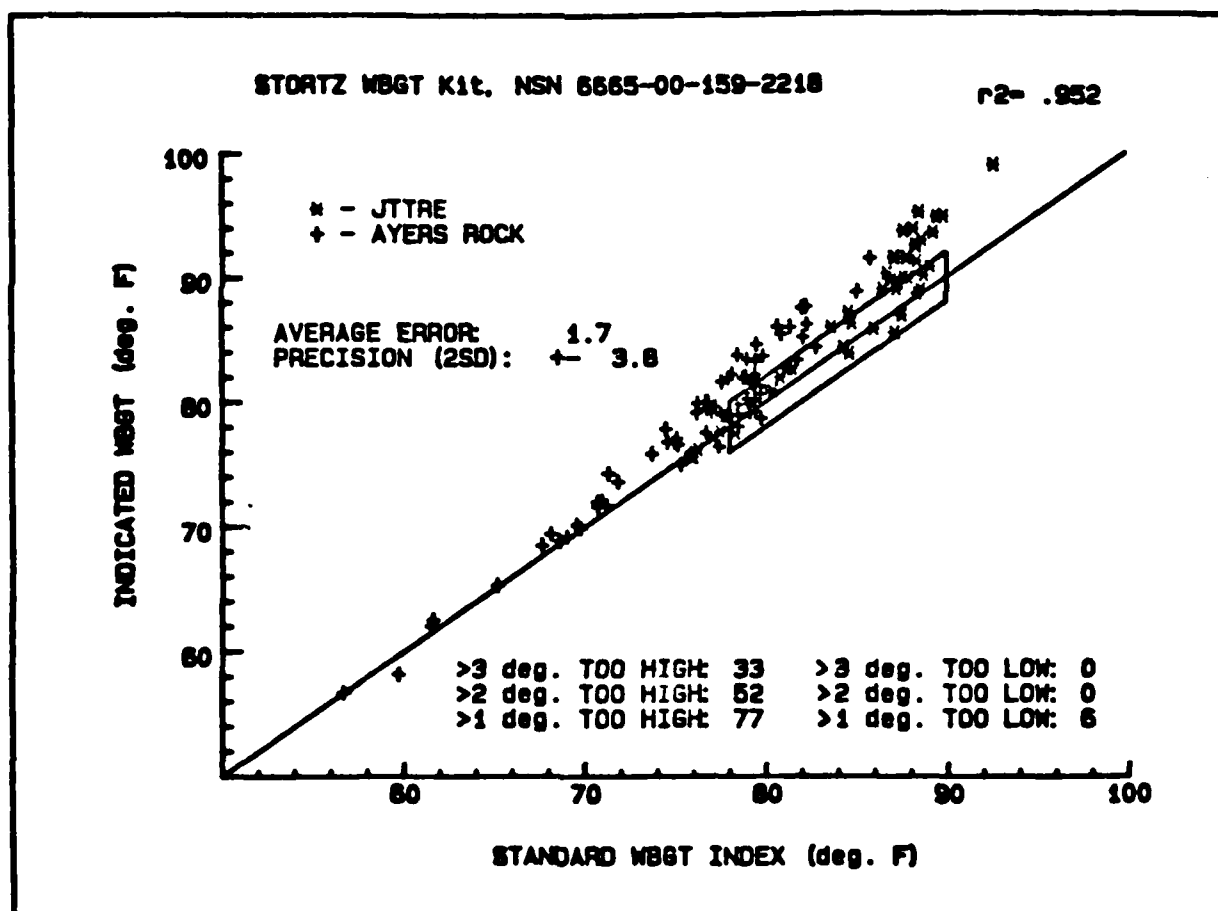

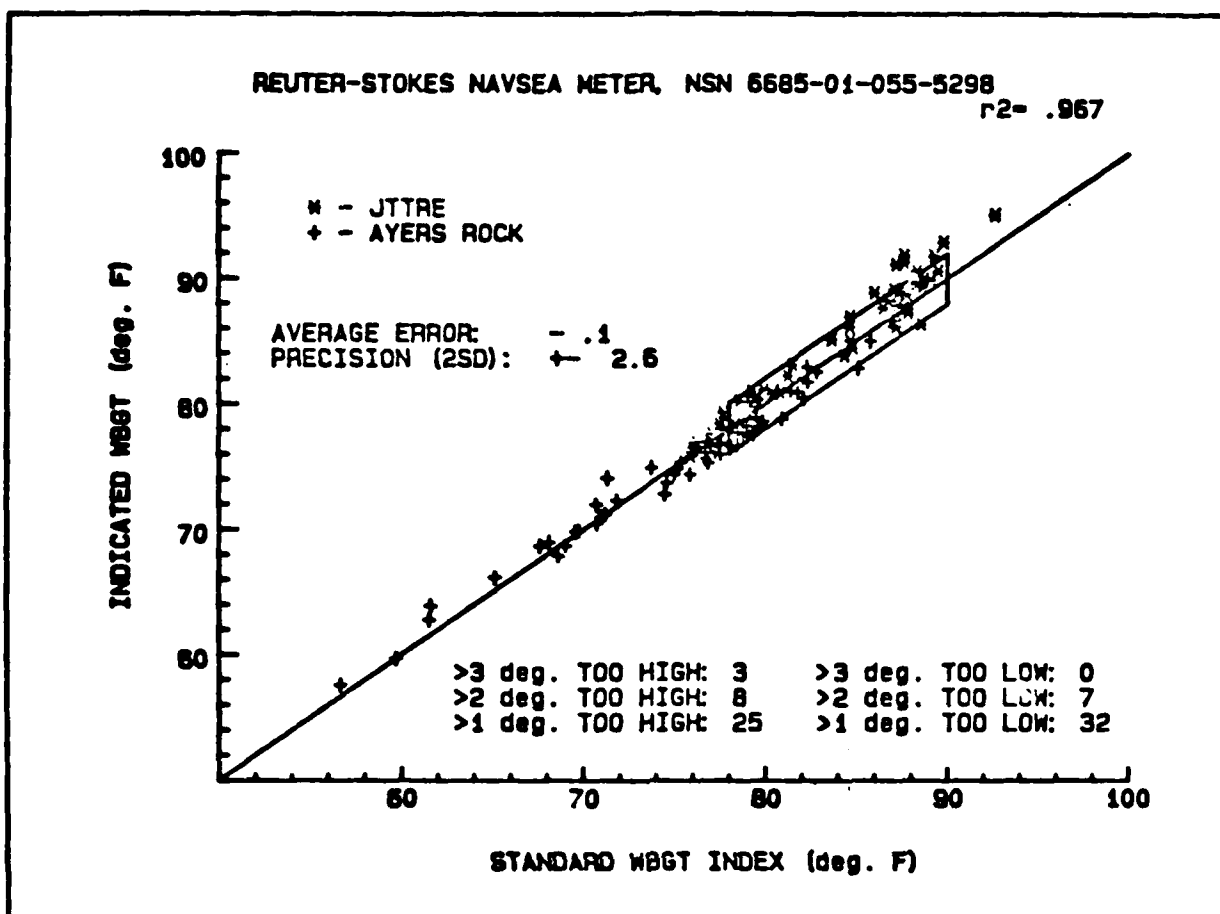Fig. 2 Accuracy of Stortz WBGT Kit relative to Standard WBGT Apparatus.

Fig. 3 Accuracy of Reuter-Stokes NAVSEA Meter relative to Standard WBGT Apparatus.

4. Error Components:

Table 1 summarizes the measured accuracy components which contibute to the overall accuracy of the computation procedure and also lists the overall accuracy of the alternative WBGT instruments.

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Table 1. Summary of Accuracy Evaluations

System or Element	Average Error ($\bar{D}$ statistic)		Precision (± 2 SD of $\bar{D}$)	
	°F	(°C)	°F	(°C)
A. Overall (vs Standard WBGT)				
Botball correction procedure				
(in the field)	+2.6	(1.4)	+2.9	(1.6)
(in the wind tunnel study)	-0.1	(0.1)	±1.6	(0.9)
B. Measured Error Components				
Botsball dial thermometer	+0.1	(0.1)	±0.6	(0.3)
(vs Quartz Thermometer, Lab Cal)				
Dial thermometer DB measurement	-0.4	(0.2)	±3.8	(2.1)
(vs dry bulb of Standard WBGT)				
Botsball readings, inter-instrument variability	------		±1.1	(0.6)
C. Alternative WBGT Instruments				
Reuter-Stokes, NAVSEA Meter				
(in the field)	-0.1	(0.1)	±2.6	(1.4)
(in the wind tunnel study)	+0.5	(0.3)	±1.1	(0.6)
Stortz WBGT Kit				
(in the field)	+1.7	(0.9)	±3.8	(2.1)
(in the wind tunnel study)	-0.7	(0.4)	±0.9	(0.5)

VIII. DISCUSSION

1. Accuracy Performance of the Procedure in the Field:

In comparison to the accuracy performance of the Botsball correction procedure in the wind tunnel tests, field evaluations showed considerable deterioration. Nevertheless, from the standpoint of safety, these decriments in overall accuracy were compensated by the fact that the increased average errors were in the positive direction and therefore resulted in overestimates of WBGT rather than underestimates. In no instance did the proposed Botsball correction procedure underestimate the prevailing WBGT (as measured by the full size, standard WBGT apparatus) by more than $2^{O}F$ ($1.1^{O}C$). Although this overly conservative correction of the Botsball reading needs to be addressed, several factors should be kept in mind with respect to potential alterations of the procedure itself.

    a. Data Set Limitations: While conditions at the jungle test site spanned the full range of doctrine relevent WBGT readings between 78 and $90^{O}F$ ($26-32^{O}C$), the maximum standard WBGT reading obtained at the desert site was $85.5^{O}F$ ($29.7^{O}C$). Thus, there is a gap in the data set with respect to the most severe desert heat stress environments.

    b. Temporal Uniformity of Heat Stress Environments: The fall off in overall accuracy seen in the progression from wind tunnel results to field results probably reflects, at least in part, the dynamic minute-to-minute variations in natural heat stress environments. Over the course of one measurement cycle, typically 4 minutes, we found fluctuations in the standard WBGT index which averaged $1.9^{O}F$ ($1.0^{O}C$) in the jungle and $0.9^{O}F$ ($0.5^{O}C$) in the desert. Differences in the response times of the instruments and sensors may be expected to produce 'lag' effects on precision assessments that were not an issue in the wind tunnel tests where conditions were 'clamped'. Our experience in this regard only serves to underscore the absolute necessity for field testing of laboratory results. From a practical point of view, it seems likely that some allowance for the dynamic characteristics of natural environments should be made to establish realistic accuracy criteria for the acceptability of the Botsball correction procedure or any other heat stress assessment methodology.

2. Accuracy Requirements to Support Existing Doctrine:

Dramatic changes in physiological limitations and water requirements occur in the WBGT index region between $78-90^{O}F$ ($26-32^{O}C$). Within this $12^{O}F$ ($6.7^{O}C$) zone are 4 bands, ranging from $2^{O}F$ ($1.1^{O}C$) to $4^{O}F$ ($2.2^{O}C$) in width, for which specific military guidance on work/rest cycles and hourly

water consumption rates have been established (2). The measurement accuracy bandwidth limit for resolving the narrowest band is therefore $\pm1^{\circ}F$ ($0.6^{\circ}C$). This level of accuracy was not obtained with any instrument during the course of this study and is probably not obtainable over the full range of heat stress environments with even the most expensive equipment. Nevertheless, the development of more accurate local heat stress assessment capabilities is an essential element in the effective implementation of military hot weather doctrine.

IX.   CONCLUSIONS AND RECOMMENDATIONS

1.   It is technically feasible to obtain a reasonable estimate of the prevailing shaded dry bulb temperature using the dial thermometer component of the Botsball and a 3 minute equilibration time.

RECOMMEND: User level evaluation of the convenience of this additional process which is necessary for implementing the Botsball 'correction' procedure.

2.   The proposed Botsball correction procedure overestimated the prevailing standard WBGT index in the Australian jungle and desert environments by, on average, $2.6^{\circ}F$ ($1.4^{\circ}C$). While the magnitude of this error is of concern, it is important to note that it is in the safe or 'conservative' direction, and, from the results thus far, the procedure appears to eliminate any possibility of underestimating the prevailing heat stress with the Botsball. In addition, since the Australian data set did not include any hot-dry desert WBGT index values above $85.5^{\circ}F$ ($29.7^{\circ}C$) and since the magnitude of the overcorrection may be reduced when those data points are added, it would not be advisable to make changes in the procedure at this time.

RECOMMEND: Proceed with user level field testing of this procedure, with no modifications at this time. Relevent Botsball and standard WBGT index data for hot-dr$_{/}$:serts in the WBGT region between $85.5^{\circ}F$ ($29.7^{\circ}C$) and $^{. ' . }F$ ($32.2^{\circ}C$) could be obtained as part of that effort.   le desert data set is complete, reassess the conversic ..racy and make any necessary adjustments to the correction equation.

3.   The two WBGT instruments currently available in the military supply system and described in TB MED 507 performed reasonably well against the full size, standard WBGT apparatus. Average error for the electronic Reuter-Stokes NAVSEA meter and the mechanical Stortz WBGT Kit were $0.3^{\circ}F$ ($0.2^{\circ}C$) and $1.7^{\circ}F$ ($0.9^{\circ}C$) respectively.   The electronic device was substantially easier to use and its precision was

superior to the mechanical device, but its use of rechargeable batteries may be a liability in field situations.

RECOMMEND: Continued search for a rugged, inexpensive, preferably off the shelf electronic WBGT meter, utilizing replaceable batteries, that could be brought into the military supply system.

ACKNOWLEDGEMENTS

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