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# The Ability of the U.S. Army Heat Strain Decision Aid (HSDA) to Predict a Limiting Heat Stress Exposure

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# The Ability of the U.S. Army Heat Strain Decision Aid (HSDA) to Predict a Limiting Heat Stress Exposure

By

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of the requirements for the degree of
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DEDICATION

This thesis is dedicated to my husband Matthew Glisson who has been a pillar of support throughout my graduate studies. Thank you for always pushing me to reach my full potential, and for believing in me even when I didn't believe in myself

To my parents Bryce and Cynthia Greer, thank you for instilling in me a good work ethic and for always reminding me of the importance of education. You never let me take the easy road because you had faith in my abilities. I could have never gotten this far in life without your love and guidance.

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LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ARIEM | A U.S. Army Research Institute of Environmental Medicine Heat Strain Prediction Model |
| ARIEM-EXP | A U.S. Army Research Institute of Environmental Medicine Heat Strain Prediction Model-Experimental |
| ACGIH | American Conference of Governmental Industrial Hygienists |
| AUC | Area Under the Curve |
| $E_{max}$ | Maximum rate of evaporative cooling |
| $E_{req}$ | Evaporation required to maintain equilibrium |
| fHSDA | Heat Strain Decision Aid Function |
| HSI | Heat Stress Index |
| HSDA | Heat Strain Decision Aid |
| $i_m$ | Vapor Permeability |
| $I_T$ | Total Thermal Resistance |
| IRB | Institutional Review Board |
| ISO | International Organization for Standardization |
| MoHSM | Mobile Heat Stress Monitor |
| NIOSH | National Institute for Occupational Safety and Health |
| PHS | Predicted Heat Strain Model |
| RAL | Recommended Alert Limit |
| REL | Recommended Exposure Limit |
| ROC | Receiver Operating Characteristic |
| $T_a$ | Air Temperautre |
| $T_c$ | Core Temperature |

| | |
|---|---|
| TLV | Threshold Limit Value |
| $T_r$ | Mean Radiant Temperature |
| $T_{re}$ | Experimentally Measured Core Temperature |
| USARIEM | U.S. Army Research Institute of Environmental Medicine |
| $V_a$ | Air Velocity |
| VBA | Visual Basic for Applications |
| WBGT | Wet Bulb Globe Temperature |

# ABSTRACT

Working below the threshold limit value (TLV) for heat stress is not always feasible. When work above the TLV is required, an exposure method is needed that can help protect workers from time limiting heat stress by calculating a safe time for work at certain heat exposures. The purpose of this paper is to determine whether the USARIEM Heat Strain Decision Aid (HSDA) can be used to predict time limiting heat stress exposure in an occupational setting.

Twelve adults participated in time limited heat stress exposures. A range of heat stress conditions were designed using three different ensembles and five different heat stress levels. Safe exposure times were assigned based on limiting criteria for core temperature (38.5°C), high heart rate (90% of age-estimated maximum), or willingness to continue. The HSDA process was adapted to an Excel function using Visual Basic for Applications (VBA) and trial data were input data to the HSDA function. A second HSDA function was used to find a predicted core temperature for fixed a standard person using a height of 170cm, a weight of 70kg, and an initial core temperature of 37°C.

The logistic regression and probability of the individual data as well as the fixed data were compared. We found that the HSDA could be used to assess time limiting exposures in an occupational setting when workers are working above the TLV.

# INTRODUCTION

In the late 1700's Francois Bossier de Sauvages used the term Paraphyrosyne Calentura to describe a mental disease observed in sailors in the tropics. The characteristic symptom of this illness was delusions of the sea being the green fields of the sailor's homeland. In response to this delusion, sailors would attempt to throw themselves overboard. In the 1800's, Falret used the term "calenture" (derived from the Latin word 'calere': to be warm) to describe a feverish illness that occurred most commonly in tropical seas when the environmental conditions were hot, clear, and calm. Falret considered calenture to be a consequence of environmental factors pertaining to the weather and sea conditions (Macleod, 1983). Now days, calenture is more commonly known as heat stress.

Heat stress is a well-known occupational. Three factors influence the intensity of heat stress: Environment, work demands, and clothing. In order to predict the intensity of heat stress, a heat stress model, incorporating the risk factors listed above, can be used.

Currently, there are two types of models used to assess heat stress: empirical models and rational models. Empirical models rely on environmental monitoring such as the wet bulb globe temperature (WBGT). The wet bulb globe temperature combines the effects of humidity and air movement, air temperature and radiation, and air temperature in order to compute a value for temperature. The WBGT is the index used to calculate the ACGIH Threshold Limit Values (TLVs) as well as the NIOSH Recommended Exposure Limit (REL) and Recommended Alert Limit (RAL).

The NIOSH RELs were developed to protect most healthy workers from developing adverse, heat-related health effects (Jacklitsch B and N., 2016; Plog and Quinlan, 2012). The REL and RAL use environmental heat exposure in the form of WBGT and the metabolic rate in order to predict the time interval a worker may be able to work without experiencing adverse heat-related health effects.

While an empirical model relies on environmental factors, a rational model of heat stress relies on a model of heat balance equation based on the biophysics of heat exchange between a hypothetical person and the environment. The basic heat balance equation is

$$S = (M - W) \pm C \pm R \pm K - E$$

where

S=change in body heat

(M-W) = total metabolism minus external work performed

C = convective heat exchange

R = radiative heat exchange

K = conductive heat exchange

E = evaporative heat loss

The major modes of heat exchange between humans and the environment are convection, radiation, and evaporation. A heat balance analysis can be used to assess the risk of adverse heat-related effects. If thermal equilibrium can be established, there is no risk of excessive levels of heat stress, but if a thermal equilibrium cannot be achieved, then the amount of time required to reach the upper limit of heat storage, theoretically core temperature, can be determined (Plog and Quinlan, 2012).

An early rational model for predicting heat stress was the Heat Stress Index (HSI). The HSI was proposed in 1955 by Belding and Hatch (Belding and Hatch, 1955) and is based on a relationship between the amount of evaporation required to maintain thermal equilibrium ($E_{req}$) and the maximum rate of evaporative cooling that can take place ($E_{max}$). Over the years the understanding of heat exchange and human limits have seen an evolution from HSI to the Predicted Heat Strain model (PHS) (ISO, 2004; Malchaire et al., 2001) and the Heat Strain Decision Aid (HSDA) (Potter et al., 2017).

The PHS is a rational method of heat balance analysis that is used to determine the amount of evaporative cooling required for thermal equilibrium ($E_{req}$), whether sufficient cooling can be achieved by sweating and evaporation, and the time limits required if sweating or evaporation are not sufficient for thermal equilibrium (ISO, 2004; Malchaire et al., 2001). The Heat Strain Decision Aid was developed by the US Army to predict core temperature in response to occupational heat exposures (Kraning, 1995). Like PHS, the HSDA uses environmental facts, clothing characteristics, work demands, and time to predict the core temperature of an individual. The HSDA model improves on HSI and PHS in that it predicts not only the maximum one-time exposure, but also the work rest cycle time and recovery time.

The purpose of this study is to evaluate the ability of the HSDA to predict a limiting heat stress exposure in an occupational environment by comparing fixed personal data to individual personal data.

# LITERATURE REVIEW

Over the past 100 years, several indices and models have been developed as a way to predict the level of heat stress that a worker might experience in certain jobs. For all of the indices, the level of metabolic heat production is either directly incorporated into the index, or the acceptable index values varies as a function of heat production (Jacklitsch B and N., 2016).

In the 1990s, the U.S. ARMY Research Institute of Environmental Medicine (USARIEM) developed a heat strain model known as The USARIEM Heat Strain Model (Kraning, 1995). This model used empirically derived equations to predict physiological responses during heat exposure. The original model required energy expenditure, environmental conditions, and clothing data to predict rectal temperature, heart rate, and sweat loss.  The rectal temperature was used to predict the core temperature at any given time during exercise as well as a core temperature at equilibrium. This model was adapted for use on personal computers in a version known as the Heat Strain Decision Aid (HSDA) (Cadarette and Stroschein, 1999).

In 1995 Kraning assembled data from six different studies in order to review the designs of three different models used at USARIEM (Kraning, 1995). During his study, Kraning found that the USARIEM consistently over predicted the actual temperature rise in four out of the five studies, sometimes over predicting the temperature by as much as 1°C. This occurred because the lag time for rise in core temperature resulted in a sudden rise in predicted core temperature at the beginning of exercise (Cadarette and Stroschein, 1999; Kraning, 1995).

In 1997, Gonzalez et al (Gonzalez et al., 1997) conducted a study comparing core temperature responses to exercise times in various ensembles. During this study, a few limitations of the USARIEM Heat Strain Model were found. The first limitation was that the equations were based on predictions tested within a finite rage of environments. Another limitation was the conservative nature of the model in over predicting heat casualties based on final estimated $T_c$ of an average population of individuals. Fit, experienced individuals often exceeded tolerance time periods and reached higher levels of $T_c$ than predicted without heat strain problems (Gonzalez et al., 1997). It was determined during this experiment that the time lag for rise in core temperature during work in the heat resulted in too abrupt a rise in the predicted core temperature at the onset of exercise (Cadarette and Stroschein, 1999). A time delay feature was added into the model which effectively buffered the abrupt rise in core temperature. This calculation was the difference between the ARIEM model and the ARIEM-EXP model.

Toward the end of 1990's, Cadarette (Cadarette and Stroschein, 1999) performed a cross validation of the core temperature portion of the ARIEM, HSDA, and ARIEM-EXP. Cadarette hypothesized that all models would provide a valid, but conservative estimate of core temperature and heat tolerance in healthy, young, heat acclimated males. Cadarette also predicted that the ARIEM-EXP would more closely predict core temperature changes in the initial phase of exercise. The results of this study showed, once again, that the ARIEM and HSDA models do not closely predict core temperature over the course of 3 hour heat stress experiments due to the abrupt, initial rise of core temperature. Cadarette did note that this over prediction was a safety feature built into the model for individuals performing duties in the field where lives may be at stake, but an additional problem with the models used was the presumption that allowing exercise to a core temperature of 40°C would result in a 50% casualty rate (Cadarette and Stroschein, 1999).

In 2008, a technical report regarding the HSDA was completed by USARIEM. In this report the HSDA was compared to a variant of the HSDA called the Mobile Heat Stress Monitor (MoHSM) as well as the Army's WBGT-based Flag Doctrine (Blanchard and Santee, 2008). The Flag Doctrine uses certain flag colors to represent different work/rest cycles. This technical report found that the HSDA, MoHSM, and Flag Doctrine correlated at higher WBGTs and lower workloads, but simulations for the same work rates and environmental conditions resulted in predictions that could vary as much as 230 minutes for maximum work and as much as 50 min/hr for work rest cycles

In January of 2017, Potter et. al. wrote a paper titled "Mathematical prediction of core body temperature from environment activity, and clothing: The heat strain decision aid (HSDA)". This paper traced the development of the HSDA and detailed how the HSDA uses 16 inputs and 4 elements in order to predict core temperature rise over time. These four elements were anthropometrics, environmental conditions, clothing biophysics, and work rate. The clothing biophysics included thermal resistance ($I_T$) and evaporative potential ($i_m$) as well as a gamma coefficient. In order to calculate gamma, thermal resistance evaporative potential were collected at multiple wind velocity conditions (Potter et al., 2017).

## METHODS

Twelve adults participated in the time-limited heat stress exposures. Table I provides descriptive statistics for age, height, weight, and body surface area by men, women, and combined. Participants provided a written informed consent following IRB guidelines. As noted in the table, two participants (both men) completed only half the assigned trials (seven for one and eight the other); and four subjects repeated trials on some combinations of ensemble and heat stress level.

TABLE I. Participant Characteristics as Mean ± Standard Deviation

| | Number | Age (yr) | Height (cm) | Weight (kg) | Body Surface Area ($m^2$) |
|---|---|---|---|---|---|
| Men | 8 | 33 ± 10 | 181 ±4 | 95 ± 10 | 2.15 ± 0.09 |
| Women | 4 | 28 ± 9 | 160 ± 7 | 66 ± 27 | 1.67 ± 0.33 |
| All | 12 | 32 ± 10 | 174 ± 11 | 85 ± 22 | 1.99 ± 0.30 |

Note: Two men completed about one-half the assigned trials. All other participants completed all 15 trials. There were 9 replicated trials among four of the participants.

Prior to beginning the experimental trials to determine safe exposure time, participants underwent five 120-min acclimatization sessions in dry heat (50°C, 20% relative humidity [rh]) at the same metabolic rate as the experimental trials (190 W $m^{-2}$) during which they wore a base ensemble of shorts, underwear, tee-shirt (or sports bra for women), socks, and shoes. The three different clothing ensembles included in the current study were (1) work clothes (135 g $m^{-2}$ [6 oz] cotton shirt and 270 g $m^{-2}$ [8 oz]

cotton pants), (2) water-barrier, vapor-permeable coverall (NexGen LS 417), and (3) vapor-barrier coverall (Tychem QC, polyethylene-coated Tyvek). The limited-use coveralls had a zippered closure in the front and elastic cuffs at the arms and legs, and they did not include a hood. Each of the trial ensembles was worn over the base ensemble. The design of the study was to include a range of heat stress conditions for which the participants were not expected to reach 120 min. Five heat stress levels were selected starting with a value (L1 in Table II) that was nominally 1°C-WBGT higher than the critical WBGT for that clothing ensemble at 50% relative humidity based on previous work,(Bernard et al., 2007) and about 7°C-WBGT above the TLV. From our experience, the L1 level should result in the loss of thermal equilibrium (uncompensable heat stress) for most participants, but not all. That is, it was expected that safe exposure times would be in the vicinity of 100 to 120 min, and the trial period was limited to 120 min. The following levels (L2 through L5) were approximately 1.0, 2.5, 4.5, and 8.0°C-WBGT greater than the L1 level. These were expected to produce progressively shorter safe exposure times. The 15 combinations of clothing and heat stress level were assigned to participants in random order. Table II gives the number of trials and the actual normalized metabolic rates and WBGTs (± standard deviation) by clothing ensemble and heat stress level. There were 15 combinations of clothing and environment, and each participant was scheduled for trials for each combination in a partially balanced design to minimize the effects of trial order.

TABLE II. Number of Observations, Normalized Metabolic Rate (W $m^{-2}$), and WBGT (°C-WBGT)(mean ± standard deviation) at 50% Relative Humidity for Combinations of Clothing Ensemble and Heat Stress Level

| | Heat Stress Level | | | | |
|---|---|---|---|---|---|
| Ensemble | L1 | L2 | L3 | L4 | L5 |
| Work Clothes | | | | | |
| N | 11 | 13 | 13 | 13 | 12 |
| M (W $m^{-2}$) | 187±16 | 183±21 | 194±24 | 188±20 | 190±24 |
| WBGT (°C) | 36.0±0.6 | 36.8±1.0 | 38.2±0.7 | 40.1±0.9 | 43.8±1.2 |
| NextGen | | | | | |
| N | 11 | 12 | 10 | 11 | 9 |
| M (W $m^{-2}$) | 183±15 | 188±19 | 185±18 | 181±20 | 188±21 |
| WBGT (°C) | 33.1±0.5 | 33.9±0.6 | 36.0±1.0 | 37.8±0.9 | 41.1±0.5 |
| Tychem QC | | | | | |
| N | 10 | 11 | 12 | 12 | 15 |
| M (W $m^{-2}$) | 180±15 | 175±17 | 182±22 | 180±23 | 187±22 |
| WBGT (°C) | 29.5±0.4 | 30.3±1.1 | 32.0±1.5 | 33.7±0.6 | 37.8±1.5 |

Each participant walked on a treadmill at a moderate rate of work (target of 190 W $m^{-2}$). During trials, participants were allowed to drink water or Gatorade at will. Core temperature ($T_c$), heart rate and ambient conditions were monitored continuously and recorded every 5 min. Metabolic rate was calculated from oxygen consumption, which was sampled one to three times during the trial at approximately 30-min intervals. The safe exposure time was taken as the time at which the first of the following conditions was satisfied: (1) $T_c$ reached 38.5°C, (2) a sustained heart rate greater than 85% of the age-predicted maximum heart rate (0.85*[220-Age]), or (3) participant wished to stop. The third criterion was included because a participant may experience fatigue or the early symptoms of heat-related disorders prior to reaching a physiological limit. This was also a participant safety requirement.

The HSDA process as implemented in the Excel workbook (Potter et al., 2017) was adapted for this project to an Excel function using Visual Basic for Applications

(VBA). The code is included in the appendix A. Because manikin data for the three ensembles included only one air velocity, the USARIEM method to estimate the gamma-value was used. The formula used to estimate gamma is as follows:

$$y = a * v^g$$

where y = the specific line; a = the initial point or constant; v = rate of exponential growth; and g = growth coefficient (Potter et al., 2014). Table III shows the gamma values used in this experiment.

TABLE III. Clothing Biophysical Characteristics

| **Description** | **IT(clo)** | **im ($m^2$k/w)** | **ITVg** | **im/cloVg** |
|---|---|---|---|---|
| Cotton Work Clothes | 1.200 | 0.360 | -0.27 | 0.30 |
| NexGen Coveralls w/o hood | 1.187 | 0.270 | -0.23 | 0.26 |
| Tychem QC Coveralls w/o hood | 1.213 | 0.130 | -0.15 | 0.19 |

Globe temperature was used as a data entry option to account for the radiant environment. Mean radiant temperature ($T_r$) was calculated using the forced convection formulation(Parsons, 2014) as follows:

$$T_r = [(T_g + 273)^4 + \frac{1.1 \cdot 10^8 \cdot \upsilon_a{}^{0.6}}{\varepsilon \cdot D^{0.4}} (T_g - T_a)]^{0.25} - 273$$

Because there were trial conditions in which the water vapor pressure exceeded the estimated saturated water vapor pressure at skin temperature, $E_{max}$ would become negative and cause a computation error. In order to avoid this error, $E_{max}$ was forced to 0.1 W if $E_{max}$ was ≤ 0.

The HSDA function (fHSDA) was designed to return a value for predicted core temperature ($T_c$) at a specified time. For each trial, fHSDA was used to find a predicted

$T_c$ using the individual and trial heat stress exposure data. For the individual data, height, weight, metabolic heat production, and initial core (rectal) temperature was provided to the function along with air temperature ($T_a$), mean radiant temperature ($T_r$) and air velocity ($V_a$). Vapor permeability ($i_m$) and total thermal resistance ($I_T$) were determined from manikin test for the clothing ensembles. A second fHSDA prediction of $T_c$ was determined for fixed individual values (ht = 170cm; wt = 70 kg; and initial $T_c$ = 37°C). The exposure time used by the function was the noted time at the first instance of the *a priori* decision criteria being met. The dependent variable was $T_c$ from fHSDA. The independent variables were the trial data. All of the n observations of $T_c$ were rank-ordered from lowest to highest. From the rank order, the probability (p) of $i^{th}$ observed value was i/(n+1). The odds were computed as $p_i$ / (1 – $p_i$); and then the ln(odds) was computed. The logistic regression was the linear regression of $T_c$ on ln(odds).

To estimate the relationship between sensitivity and specificity, the predicted $T_c$ was noted for each trial at 10 min prior to the exposure time limit (non-case) and 10 min after the exposure time limit (case). A logistic regression on the non-case v case status was used to find the area under the receiver operating characteristic (ROC) curve (AUC).

# RESULTS

The distribution of termination criteria by heat stress level across all three clothing ensembles is provided in Table 4. See Table 5 for the distributions of exposure times by heat stress level and clothing ensemble.

TABLE IV. Reasons for Assigning the Safe Exposure Time by Ensemble and Heat Stress Level

| | Heat Stress Level | | | | |
|---|---|---|---|---|---|
| Ensemble | L1 | L2 | L3 | L4 | L5 |
| **Work Clothes** | | | | | |
| Temperature | 8 | 10 | 8 | 9 | 5 |
| HeartRate | 2 | 3 | 4 | 4 | 6 |
| Fatigue | 1 | | 1 | | 1 |
| Time = 120 | | | | | |
| **NexGen** | | | | | |
| Temperature | 5 | 4 | 7 | 7 | 6 |
| HeartRate | 2 | 2 | 2 | 3 | 3 |
| Fatigue | 2 | 1 | 1 | 1 | |
| Time = 120 | 2 | 5 | | | |
| **Tychem QC** | | | | | |
| Temperature | 7 | 7 | 9 | 8 | 8 |
| HeartRate | 3 | 4 | 3 | 3 | 7 |
| Fatigue | | | | 1 | |
| Time = 120 | | | | | |
| **All** | | | | | |
| Temperature | 20 | 21 | 24 | 24 | 19 |
| Heart Rate | 7 | 9 | 9 | 10 | 16 |
| Fatigue | 3 | 1 | 2 | 2 | 1 |
| Time = 120 | 2 | 5 | | | |

TABLE V. Mean (± standard deviation) for Safe Exposure Times for the Three Clothing Ensembles by Five Heat Stress Levels

| | Mean ± Standard Deviation of Safe Exposure Time (min) | | | |
|---|---|---|---|---|
| Heat Stress Level | Work Clothes | NextGen | Tychem QC | Least Squares Mean[A] |
| L1 | 78 ± 17 | 77 ± 30 | 77 ± 14 | 77 |
| L2 | 61 ± 20 | 97 ± 28 | 62 ± 20 | 63 |
| L3 | 55 ± 16 | 49 ± 14 | 56 ± 13 | 53 |
| L4 | 38 ±8 | 40±8 | 47±6 | 42 |
| L5 | 26 ±7 | 28±9 | 33±7 | 28 |
| Least Squares Mean[A] | 50 | 53 | 55 | |

[A]Least square means exclude data from NexGen at Heat Stress Level L2 (shaded cell). Least square means account for missing data and represent the basis for multiple comparison testing.

The HSDA includes both personal and job data to predict a body core temperature. The plot of probability of a limiting heat stress exposure by predicted core temperature is shown in Figure 1. The logistic regression for the data is $\ln(p/(1-p)) = -94.3 + 2.43\ T_c$, and the logistic regression line is also shown in the figure.

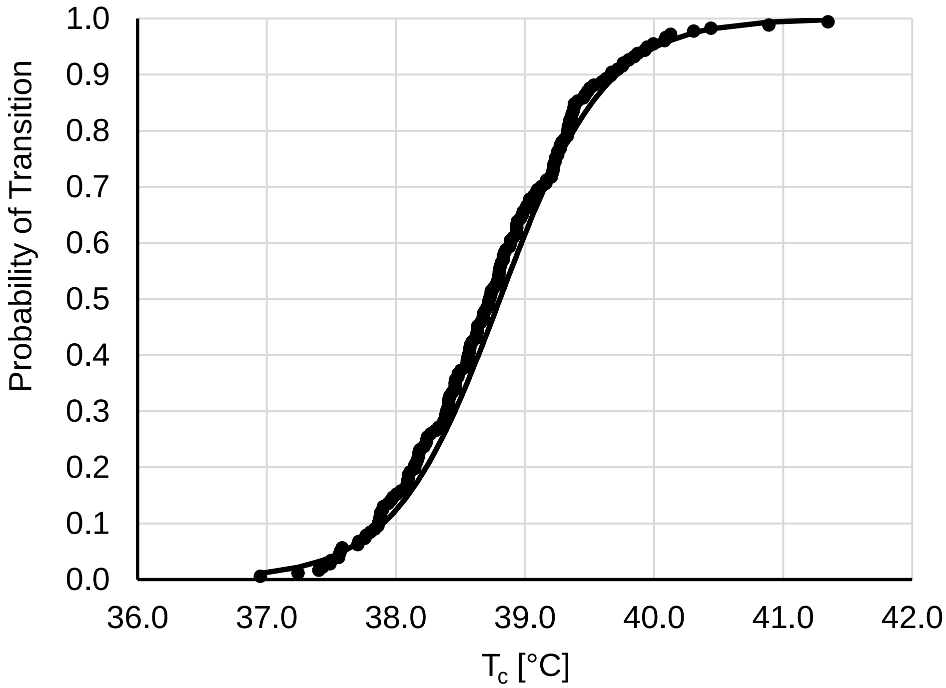


Figure 1. Probability of a limiting heat stress exposure for individual data by predicted core temperature ($T_c$).

To evaluate the effectiveness of the HSDA on a group of individuals, job data was used along with fixed personal data (ht = 170 cm, wt = 70 kg, initial core temperature = 37°C) to predict a body core temperature. The plot of probability of a limiting heat stress exposure by predicted core temperature is shown in Figure 2. The logistic regression for the data is ln(p/(1-p)) = -95.1 + 2.47 Tc, and the logistic regression line is also shown in the figure.

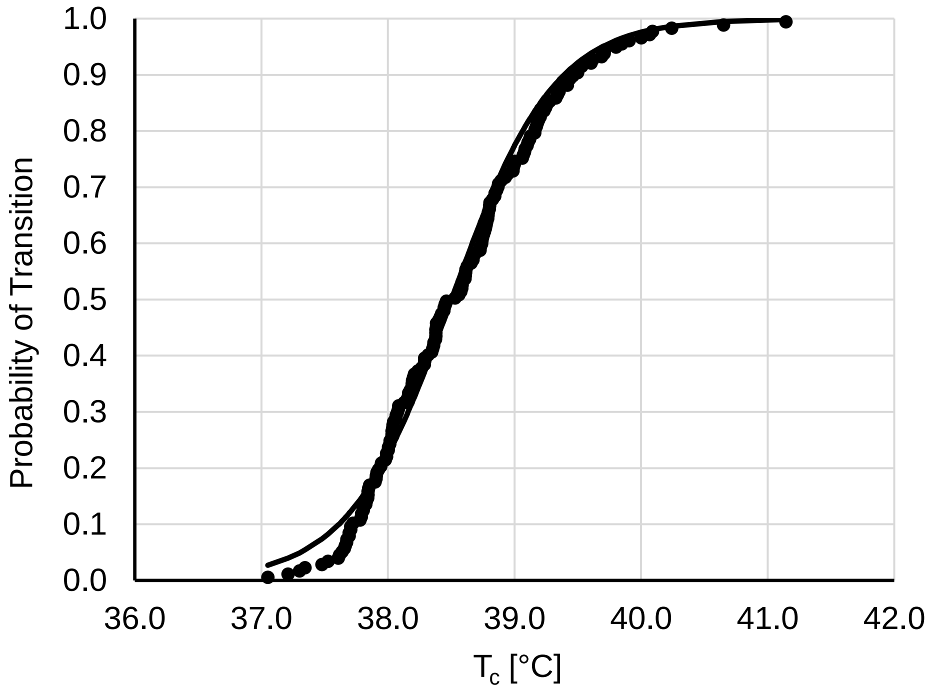


Figure 2. Probability of a limiting heat stress exposure for fixed personal data by predicted core temperature ($T_c$).

# DISCUSSION

The data from this experiment covers a wide range of environments and ensembles. Three different ensembles ranging from everyday wear (woven fabric) to microporous wear, to vapor barrier wear were tested under five different levels of time limited heat stress (see Table 4). Using a range of clothing in a range of environments increases the validity of this experiment.

The American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) for body core temperature is 38.5°C for an acclimatized, healthy individual. This level is more stringent than the military standard since the TLV aims to protect a large group of individuals varying in personal data such as height, weight, age, and health.

The HSDA has evolved to predict the mean of a limiting heat stress exposure (Potter et al., 2017). These aids are based on mean responses which are good for building a model, but do not help when prescribing a time limit that is protective of most. The logistic regression shows the probability of a limiting heat stress exposure, but the dose-response curves provide insight into whether the HSDA can be used to predict a limiting heat stress exposure for a general population (see Table V).

TABLE VI. Probability of a Limiting Heat Stress Exposure

| | Tc[C°] | |
|---|---|---|
| Probability | Individual Data | Fixed Data |
| 5% | 37.6 | 37.6 |
| 10% | 37.9 | 37.7 |
| 25% | 38.2 | 38.0 |

Any practical occupational use of the HSDA cannot use personal data since predictions will be made for a group of individuals where it is unlikely to know personal data such as core temperatures. For industrial hygiene practice, it is our goal to protect 90-95% of the population.  Table VI. shows that it is possible to use fixed data as an entry into the HSDA and still calculate work times above the TLV that will be protective to most.

There are differences in how this aid will be used for occupational settings compared to the USARIEM recommendations. The USARIEM aims to predict the level at which an individual will have a limiting heat stress exposure due to heat exhaustion while this aid in an occupational setting would be used as a way to protect a large group who are working above the TLV. This aid remains to be a way of protecting workers when they are working above the TLV.

The limitations of this study are that the group of individuals tested are relatively young and, while they may be less fit than a military group, they are more fit than the average worker. Another limitation is that the fixed data was not fully explored to see whether it was a good representation of a standard person. It is important to note that our individuals were acclimatized workers, so the results may not apply to an unacclimatized worker.

# CONCLUSIONS

This study covered multiple heat stress situations. The probabilities collected from the dose-response curve of the personal data and the fixed data demonstrated that the HSDA is a helpful tool for predicting time limited exposures of heat stress when working in conditions above the TLV. The HSDA risk profile does not change when a generalized or fixed model is used in place of personalized data.

# REFERENCES


Belding, H.S., Hatch, T.F., 1955. Index for Evaluating Heat Stress in Terms of Resulting Physiological Strain. Heating Piping Air Conditioner 27, 129-136.

Bernard, T.E., Caravello, V., Schwartz, S.W., Ashley, C.D., 2007. WBGT Clothing Adjustment Factors for Four Clothing Ensembles and the Effects of Metabolic Demands. Journal of Occupational and Environmental Hygiene 5, 1-5.

Blanchard, L., Santee, W., 2008. Comparison of USARIEM Heat Strain Decision Aid to Mobile Decision Aid and Standard Army Guidelines for Warm Weather Training. U.S. Army Research Institute of Environmental Medicine, Natick, MA.

Cadarette, B.S., Kolka, M. A., Montain, S. J.,, Stroschein, L., Matthew, W., & Sawka, M. N., 1999. Cross Validation of USARIEM Heat Strain Prediction

Models. Aviation Space and Environmental Medicine 70, 996-1006.

Gonzalez, R.R., McLellan, T.M., Withey, W.R., Chang, S.K., Pandolf, K.B., 1997. Heat strain models applicable for protective clothing systems: comparison of core temperature response. Journal of Applied Physiology 83, 1017-1032.

ISO, 2004. Standard No. 7933.

Jacklitsch B, W.W., Musolin K, Coca A, Kim J-H,, N., T., 2016. NIOSH criteria for a recommended standard:

occupational exposure to heat and hot environments. U.S. Department of Health and Human Services, Centers

for Disease Control and Prevention, National Institute for Occupational Safety

and Health, DHHS (NIOSH) Cincinnati, OH.

Kraning, K.K., II., 1995. Validation of Mathematical Models for Predicting

Physiological Events During Work and Heat Stress U.S. Army Research Institute of Environmental Medicine, Natick, MA.

Macleod, A.D., 1983. Calenture-missing at sea? Br J Med Psychol 56 ( Pt 4), 347-350.

Malchaire, J., Kampmann, B., Mehnert, P., Gebhardt, H., Piette, A., Havenith, G., Holmer, I., Parsons, K., Alfano, G., Griefahn, B., 2001. Assessment of the Risk of Heat Stress Disorders Encountered During Work in Hot Conditions. Int Arch Occup Environ Health 75, 153-162.

O'Brien, C., Cadarette, B.S., Endrusick, T.L., Blanchard, L.A., Xu, X., Berglund, L.G., Sawka, M.N., Hoyt, R.W., 2008. General Procedure for Protective Clothing and Equipment Evaluations Relative to Heat and Cold Stress. U.S. Army Research Institute of Environmental Medicine, Natick, MA.

Parsons, K., 2014. Human Thermal Environments, Third ed. CRC Press, Boca Raton, FL.

Plog, B.A., Quinlan, P.J., 2012. Fundamental of Industrial Hygiene, 6 ed. National Safety Council, Itasca, IL.

Potter, A.W., Blanchard, L.A., Friedl, K.E., Cadarette, B.S., Hoyt, R.W., 2017. Mathematical prediction of core body temperature from environment, activity, and clothing: The heat strain decision aid (HSDA). Journal of Thermal Biology 64, 78-85.

Potter, A.W., Gonzalez, J.A., Karis, A.J., Rioux, T.P., Blanchard, L.A., Xu, X., 2014. Impact of Estimating Thermal Manikin Derived Wind Velocity Coefficients on Physiological Modeling. U.S. Army Research Institiute of Environmental Medicine, Natick, MA.

# APPENDICES

# APPENDIX A:

## VISUAL BASIC CODE

```
'
Function fHSDA(Ht, Wt, M, ITc, Ta, Pa, Tg, Va, IT, im, texp)
'fHSDA reports the predicted Tc at the anticipated exposure time
'This is a USF adaptation of the USARIEM Heat Stress Decision Aid (HSDA)


'Ht, height cm
'Wt, weight kg
'M, metabolic rate W
'Wex, external work W
Wex = 0 'No external work -- Fixed for this implementation
'ITc, initial core temperature ¡C
'ITsk, initial skin temperature ¡C -- constant
ITsk = 36   'Initial skin temperature in hot conditions -- Fixed for this implementation
'DIH, days of heat stress exposure
DIH = 12    'Acclimatized -- Fixed for this implementation
'dhyd, dehydration %
dhyd = 1.24 'Average dehydration -- Fixed for this implementation
'Ta, air / dry bulb temperature ¡C
'RH, relative humidity % -- Pa entered directly
'Pa -- ambient water vapor pressure kPa -- not part of HSDA and converted to torr later
        in this function
'Tg, globe temperature to estimate mean radiant temperature ¡C
'Va, air velocity m/s
'IT, total insulation clo
'im, permeability index based on total static insulation and total static evaporative
        resistance
'texp, exposure time min


Dim outcome(480, 3)
Dim tstop As Integer


'Clear the output array
For x = 1 To 480
```

```
For y = 1 To 3
outcome(x, y) = 0
Next y
Next x


'HSDA Computed Values

'Body surface area with ht in m and wt in kg
AD = 0.007184 * (Ht ^ 0.725) * (Wt ^ 0.425) '=0.007184*(Ht^0.725)*(Wt^0.425)

' Minumum value for M set by HSDA
If M / AD < 58.2 Then M = 58.2 * AD

'Note: Veff not adjusted for AD
Veff = Va + 0.004 * (M - 105) '=Va+0.004*(M-105)

'Pa entered directly rather than through RH
'Pa = 10 ^ (8.1076 - (1750.286 / (Ta + 235))) * (RH / 100) '=10^(8.1076-
        (1750.286/(Ta+235)))*(RH/100)
Pa = 7.5 * Pa    'Convert directly entered value from kPa to Torr for HSDA

'Mean radiant temperature for forced convection (Va > 0.15 m/s), standard globe (d =
        150 mm), and emissivity = 0.95
Tmr = ((Tg + 273) ^ 4 + ((110000000 * Va ^ 0.6) / (0.95 * (150 / 1000) ^ 0.4)) * (Tg - Ta))
        ^ 0.25 - 273


'Clothing
ITVg = 0.079 * IT - 0.516 * im - 0.182    ' Single point estimate of ITVg

imcloVg = -0.068 * IT + 0.466 * im + 0.216    ' Single point estimate of im/cloVg

ITeff = IT * Veff ^ ITVg    '=IT*Veff^cloVg

imdivclo = im / IT    'IT/im

Cevap = imdivclo * Veff ^ imcloVg   '=im/clo*Veff^im/cloVg

Hrc = 6.45 * AD * (Ta - ITsk) / ITeff  ' =6.45*AD*(Ta-ITsk)/Iteff

SVPTsk = 10 ^ (8.1076 - (1750.286 / (ITsk + 235))) '=10^(8.1076-
        (1750.286/(ITsk+235)))

U = (0.41 / IT) * Veff ^ (-(0.43 + ITVg))    ' =(0.41/IT)*Veff^(-(0.43+cloVg))
```

```
Rload = (-0.071 * (Tmr - Ta) ^ 2 + 10.432 * (Tmr - Ta)) * (AD / 1.8) ' =(-0.071*(Tmr-Ta)^2+10.432*(Tmr-Ta))*(AD/1.8)

Ereq = Hrc + M - Wex + U * Rload    ' =Hrc+M-Wex+U*Rload

Emax = 14.21 * AD * Cevap * (SVPTsk - Pa)    '=14.21*AD*Cevap*(SVPTsk-Pa)
If Emax <= 0 Then Emax = 0.1    'Prevents computational error


Tcf = (36.75 + 0.004 * M + 0.0025 * U * Rload + 0.0011 * Hrc + 0.8 * Exp((0.0047 * (Ereq - Emax)))) '=(36.75+0.004*M+0.0025*U*Rload+0.0011*Hrc+0.8*EXP((0.0047*(Ereq-Emax))))

Aeff = (0.5 + 1.2 * (1 - Exp((37.15 - Tcf) / 2))) * (1 - Exp(-0.005 * Emax)) * (Exp(-0.3 * DIH)) '=(0.5+1.2*(1-EXP((37.15-Tcf)/2)))*(1-EXP(-0.005*Emax))*(EXP(-0.3*DIH))

Tcf_a = Tcf + Aeff '=Tcf+Aeff

Dtc_w = Tcf_a - ITc    '=Tcf_a-ITc

Swt = 27.9 * AD * (Ereq / AD) * (Emax / AD) ^ ((-0.455)) '=27.9*AD*(Ereq/AD)*(Emax/AD)^((-0.455))

PW = (147 + (1.527 * Ereq) - (0.87 * Emax)) * AD '=(147+(1.527*Ereq)-(0.87*Emax))*AD

TDWK = 3480 / M '=3480/M

KWK = (1 + 3 * Exp(0.3 * (ITc - Tcf_a))) / 225 '=(1+3*EXP(0.3*(ITc-Tcf_a)))/225

KWKd = KWK * (1 + 0.1 * dhyd) '=KWK*(1+0.1*dhyd)

CP = 0.015 * (Emax - Ereq) '=0.015*(Emax-Ereq)

If CP < 0 Then TDRY = 15 Else TDRY = 15 * Exp(-0.5 * CP) '=IF(CP<0,15,15*EXP(-0.5*CP))

KRY = (1 - Exp(-1.5 * Abs(CP))) / 40 '=(1-EXP(-1.5*ABS(CP)))/40

KRYd = KRY * (Exp(-0.07 * dhyd)) '=KRY*(EXP(-0.07*dhyd))


'Initial Values of outcome array

outcome(1, 1) = 0    't = 0
```

```
outcome(1, 2) = ITc    'Tc at t=0 is ITc

'Select Sheet for output data in time
'Worksheets("Output").Activate
'Sheets("Output").Cells(2, 4) = 0
'Sheets("Output").Cells(2, 5) = ITc


'Run HSDA to texp

For t = 1 To texp Step 1

x = t + 1

'Compute time lags
tlagpre = 0.5 * (t - TDWK) * (t / TDWK)
tlagpost = t - TDWK

'Select time lag
If (t - TDWK) < 0 Then tlag = tlagpre Else tlag = tlagpost

Tc_t = ITc + Dtc_w * (1# - Exp(-KWKd * tlag))

outcome(x, 1) = t

outcome(x, 2) = Tc_t

'Sheets("Output").Cells(x + 1, 4) = t
'Sheets("Output").Cells(x + 1, 5) = Tc_t

Next t


fHSDA = Tc_t


End Function
```