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Ability of the ISO Predicted Heat Strain Method to Predict a Limiting Heat Stress Exposure

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to Predict a Limiting Heat Stress Exposure

by

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of the requirements for the degree of
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DEDICATION

I would like to dedicate this thesis to my children Camila, Andrea and Daniel Prieto, without you I would have not been able to accomplish my goals.

To my wife Maria Cervantes for standing by me all these years and for providing me with the most precious gift in life.

To my parents Edgar Prieto and Marlene Dunphy for teaching me principles and believing I would withstand adversities.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
E_{max}	Maximum rate of evaporative cooling
E_{req}	Evaporation required to maintain equilibrium
fPHSTre	Predicted Core Temperature Function
HSD	Honest Significant Difference
HSI	Heat Stress Index
HSL	Heat Stress Level
i_m	Vapor Permeability
I_T	Total Thermal Resistance
IRB	Institutional Review Board
ISO	International Organization for Standardization
NIOSH	National Institute for Occupational Safety and Health
OEL	Occupational Exposure Limit
PHS	Predicted Heat Strain Model
pTre	Predicted Rectal Temperature
RAL	Recommended Alert Limit
REL	Recommended Exposure Limit
SOBANE	Risk Prevention Strategy Levels; Screening, Observation, Analysis, Expertise
SR_{req}	Required Sweat Rate
T_a	Air Temperature
T_c	Core Temperature
T_g	Globe Temperature
TLV	Threshold Limit Value
T_r	Mean Radiant Temperature
T_{re}	Rectal Temperature

V_a	Air Velocity
VBA	Visual Basic for Applications
WBGT	Wet Bulb Globe Temperature

ABSTRACT

Heat stress is one of many physical agents to which thousands of workers are under constant exposure. Oftentimes it is necessary to work above the WBGT-based heat stress exposure limits. It is therefore important to consider alternative measures that include an exposure time limit to manage the heat stress. Predicted Heat Strain (PHS) (ISO7933) is one of those alternatives. PHS uses both personal factors like height and weight and job factors of environment, metabolic rate and clothing. The purpose of this project is to determine whether the PHS is an adequate method to predict short term exposure limits.

The project's data were taken from a prior experimental study where twelve participants were exposed to five different heat stress levels while over three different clothing ensembles. A total of 15 combinations of clothing and environment were tried. The PHS process was adapted to an Excel function using Visual Basic for Applications (VBA) (called fPHSTre). fPHSTre predicted a rectal temperature (Tre) at the exposure limit using both personal and job factors and then using standard values for personal factors.

Based on analysis of variance, the fPHSTre adequately accounted for clothing, specifically evaporative resistance, using either fixed or individual data for predicted Tre on the experimental trials. In general, the PHS model could be used to reliably assess time limiting safe exposures in occupational settings for workers in hot environments.

INTRODUCTION

Every year, thousands of workers in the United States experience heat related disorders due to their occupational exposures to heat stress. Occupational heat stress exposure is very common and can occur in a wide variety of American industries and environments. Understanding heat stress is necessary to successfully control it. Three job risk factors are commonly identified as (1) environmental conditions, (2) work demands and (3) clothing. All three factors are used to classify heat stress levels.

There are currently 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). WBGT combines the effects of humidity, air movement and temperature, as well as radiant heat to represent the environment. The WBGT is the index used in the ACGIH® Threshold Limit Values® (TLV®s) as well as the NIOSH Recommended Exposure Limit (REL) and Recommended Alert Limit (RAL). These WBGT-based occupational exposure limits (OELs) were developed to protect most healthy workers from developing adverse, heat-related health effects (Jacklitsch et al., 2016; Plog and Quinlan, 2012). The WBGT-based exposure assessment methods adjust the limiting WBGT level based on metabolic rate and clothing. The threshold is set so that most exposures will be sustainable for a nominal 8-h day.

While an empirical model relies on the observed link between sustainable levels of heat stress, a rational model is based on a heat balance equation using 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 little 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 can be determined (Plog and Quinlan, 2012). In this way, rational models add time as a fourth job risk factor. Predicted Heat Strain (PHS) is a rational method of heat balance analysis that is used to determine the amount of evaporative cooling required for thermal equilibrium (Ereq), whether sufficient evaporative cooling (Emax) can be achieved, and the time limit if Ereq > Emax (ISO, 2017; Malchaire et al., 2001).

The purpose of this study is to evaluate the ability of Predicted Heat Strain (PHS) to predict a time limit to heat stress.

LITERATURE REVIEW

Heat stress is the combination of job risk factors that will in turn elicit physiological responses in the human body. As a result of the relationship between heat stress and strain, occupational health professionals have developed means to measure heat stress and interpret them in an attempt to protect workers from experiencing excessive heat strain.

Malchaire developed a hierarchical strategy to measure heat stress according to levels of expertise at work; it was named the SOBANE strategy (Malcahire, 2006). He proposed that heat stress can be screened observed, analyzed, and finally approached by at various levels of expertise. While PHS is complex, Malchaire argues that PHS can be used as a black box to reduce the needed expertise to use it.

WBGT-based exposure assessment is a useful method to assess whether heat stress is present or not. More complex, rational models are useful for understanding the contributions of various factors and predicting a safe time limit on the exposure. Early examples of rational methods are the Belding-Hatch Heat Stress Index and the ISO's Required Sweat Rate (SR_{req}). The ISO standard for SR_{req} predicted the maximum duration of work in hot environments. Since its implementation, the SR_{req} has been under scrutiny for its assumptions. Predicted Heat Strain was introduced around 2000 to address the weaknesses of SR_{req}. The new model sought to account or modify on three particular elements: 1) an increase in rectal temperature through activity in neutral environments; 2) revision of maximum wetness and sweat rates; 3) establish limits for water loss and rectal temperature. The PHS standard (ISO 7933) was re-issued in 2017.

A study seeking to validate the PHS model conducted by Malchaire et.al (2001), compared data from prior 672 laboratory and 237 field experiments. Researchers concluded that the PHS provided sufficiently accurate results accounting for sweat rate and rectal temperature.

Another study conducted by Yunyan and Rowlinson (2014), sought to implement the PHS to a heat stress management guidelines for the construction industry. The authors yielded that given the plasticity of construction environments it was inadequate to attempt controlling for heat stress on workers using only one standard. In the study, it was corroborated the feasibility to developing two tools to manage heat stress on workers while applying the PHS model conjunctively (Yunyan and Rowlinson, 2014).

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. The repeated trials were not intentionally included in the experimental design.

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. There were five clothing ensembles evaluated previously for clothing adjustment factors (Bernard et al., 2007). Of these five, three represented the range of clothing adjustments for WBGT. 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. 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 Heat Stress Level

	Heat Stress Level				
Ensemble	L1	L2	L3	L4	L5
Work Clothes (woven)					
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	40.01 ± 0.9	43.8 ± 1.2
NextGen					
N	11	12	10	11	9
M (Wm^{-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	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. Rectal temperature (Tre), 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) Tre 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 PHS model process was implemented in an Excel workbook through an Excel function using Visual Basic for Applications (VBA). The code is included in Appendix A. The validity of the function was confirmed by verifying that the values matched the test conditions in the standard.

The PHS function (fPHSTre) was designed to return a value for predicted rectal temperature (Tre) at the experimentally determined safe exposure time. For each trial, fPHSTre was used to find a predicted Tre using the individual data and trial heat stress exposure data. For the individual data, height, weight, and initial rectal temperature were provided to the function along with air temperature (T_a), globe temperature (T_g) and air velocity (V_a). Vapor permeability index (i_m) and total thermal resistance (I_T) were determined from manikin test for the clothing ensembles. A second application of fPHSTre fixed the individual data at height = 1.80 m; weight = 75 kg; and initial Tre = 36.8°C. The dependent variable was predicted Tre (pTre) from fPHSTre. The independent variables were the trial data.

All of the n observations of Tre 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 Tre on ln(odds).

RESULTS

The experimental design included five levels of heat stress and three levels of clothing. In addition, fPHSTre was determined with individual values of height, weight and initial rectal temperature (fPHS[individual]) and with fixed values for these individual factors (fPHSTre[fixed]). The mean predicted rectal temperature by heat stress level and clothing type for each computational method is provided in Table III. A three-way mixed effects analysis of variance (ANOVA) (heat stress level and clothing were fixed effects with an interaction term, and participant was a random effect) was performed using JMP v13, a statistical package published by SAS. For both computational methods, significant effects were found for both heat stress level and clothing as well as the interaction term.

The relationship among clothing ensembles at the progressively higher heat stress levels are illustrated in Figure 1 for fPHSTre[individual] and in Figure 2 for fPHSTre[fixed]. The highest heat stress level was associated with the lowest mean predicted Tre. Work clothes were associated with the lowest overall predicted Tre, but this appears to be driven by the low value at HSL5. The significant interaction was driven by work clothes at the highest heat stress level (HSL5) and by water barrier clothing at HSL2 (see Figures 1 and 2).

Table III. Mean (± standard deviation) for Predicted Rectal Temperatures by Five Heat Stress Levels, Two Computational Methods and Three Clothing Ensembles

	Mean ± Standard Deviation of Predicted Rectal Temperature (C°)	
Heat Stress Level	fPHS[individual]	fPHS[fixed]
Work Clothes		
L1	39.4 ± 0.7	39.6 ± 1.2
L2	39.5 ± 0.6	39.7 ± 1.1
L3	39.7 ± 0.5	39.9 ± 1.2
L4	39.5 ± 0.4	39.4 ± 0.7
L5	38.2 ± 0.5	37.9 ± 0.4
Water Barrier		
L1	39.2 ± 0.7	39.3 ± 1.2
L2	40.0 ± 1.0	40.1 ± 1.2
L3	39.3 ± 0.6	39.3 ± 1.1
L4	39.3 ± 0.5	39.2 ± 0.7
L5	39.0 ± 0.8	38.6 ± 1.0
Vapor Barrier		
L1	39.7 ± 0.8	39.7 ± 0.9
L2	39.5 ± 0.9	39.5 ± 1.0
L3	39.5 ± 0.6	39.7 ± 0.9
L4	39.5 ± 0.5	39.5 ± 0.5
L5	39.3 ± 0.7	39.3 ± 0.9

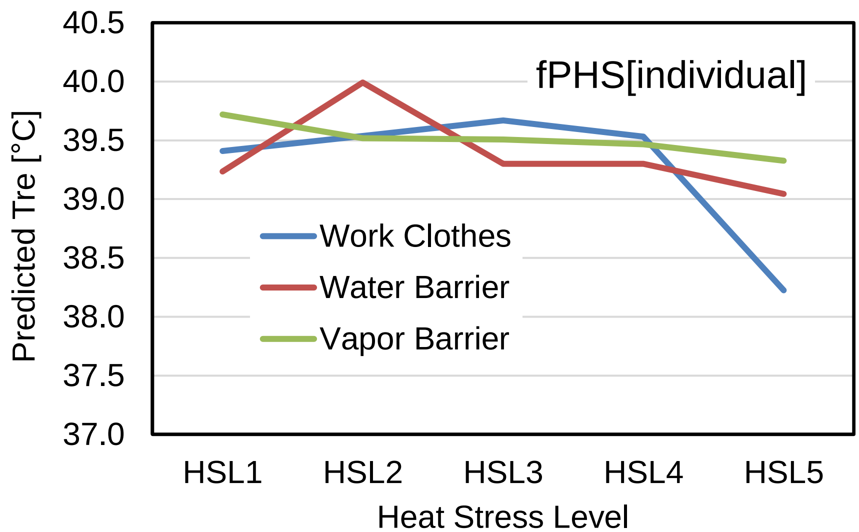

Figure 1. Predicted rectal temperature across three clothing ensembles and heat stress levels for individual data

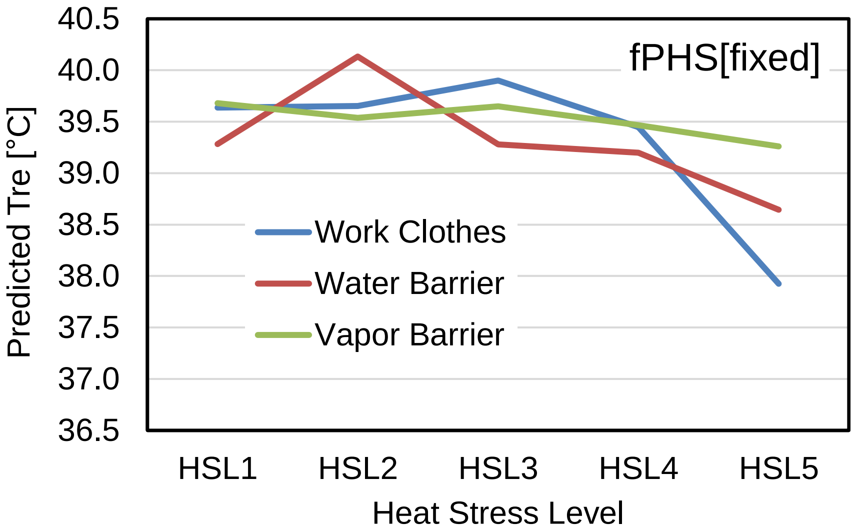

Figure 2. Predicted rectal temperature across three clothing ensembles and five heat stress levels for fixed personal data

Whether fPHSTre used individual or fixed data for the individual values, the interweaving lines in Figures 1 and 2 suggested that clothing, and specifically evaporative resistance, was adequately accounted for in the predicted Tre for the experimental trials. To examine the model generality, all three clothing ensembles were included. Based on fPHSTre[individual], the plot of probability of a transition from acceptable to unacceptable heat stress exposure by predicted rectal temperature is shown in Figure 3. The data were fit with a logistic regression, which is the line shown in the figure.

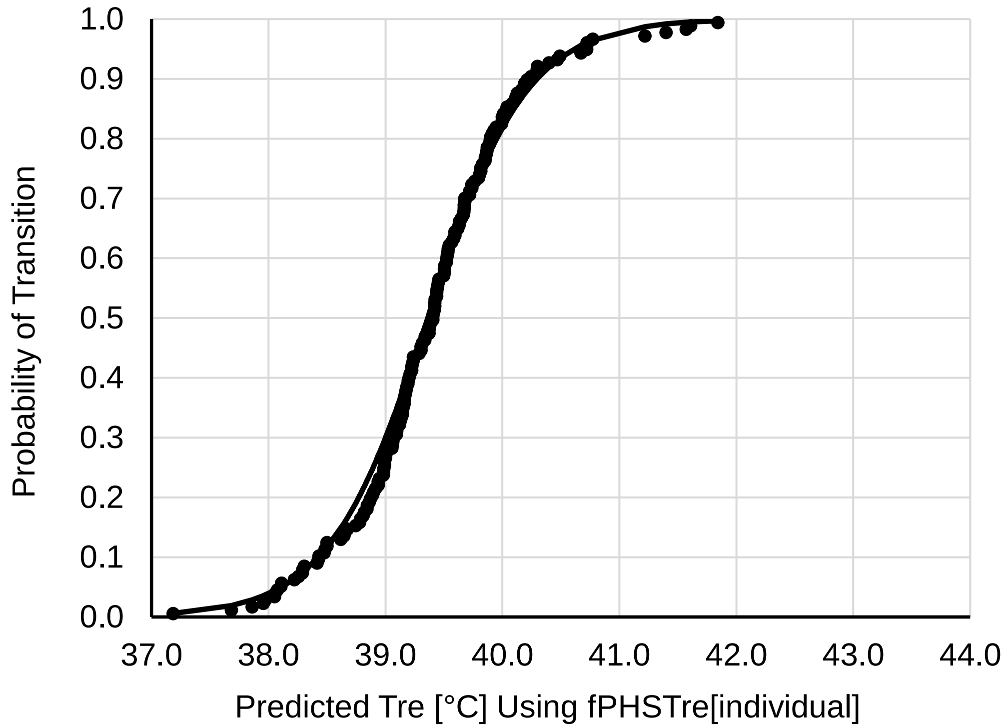

Figure 3. Probability of a limiting heat stress exposure (transition from acceptable to unacceptable) by predicted Tre using fPHSTre[individual].

Because exposure assessments usually do not include personal factors, not to mention the difficulty of knowing an initial core (or rectal) temperature, it is worthwhile treating these as fixed factors. fPHSTre[fixed] was used to evaluate the effectiveness of the PHS model on a group of individuals with fixed personal data (height = 1.8 m, weight = 75 kg, and initial rectal temperature = 36.8°C) to predict a body rectal temperature. The plot of probability of a limiting heat stress exposure by predicted rectal temperature is shown in Figure 4.

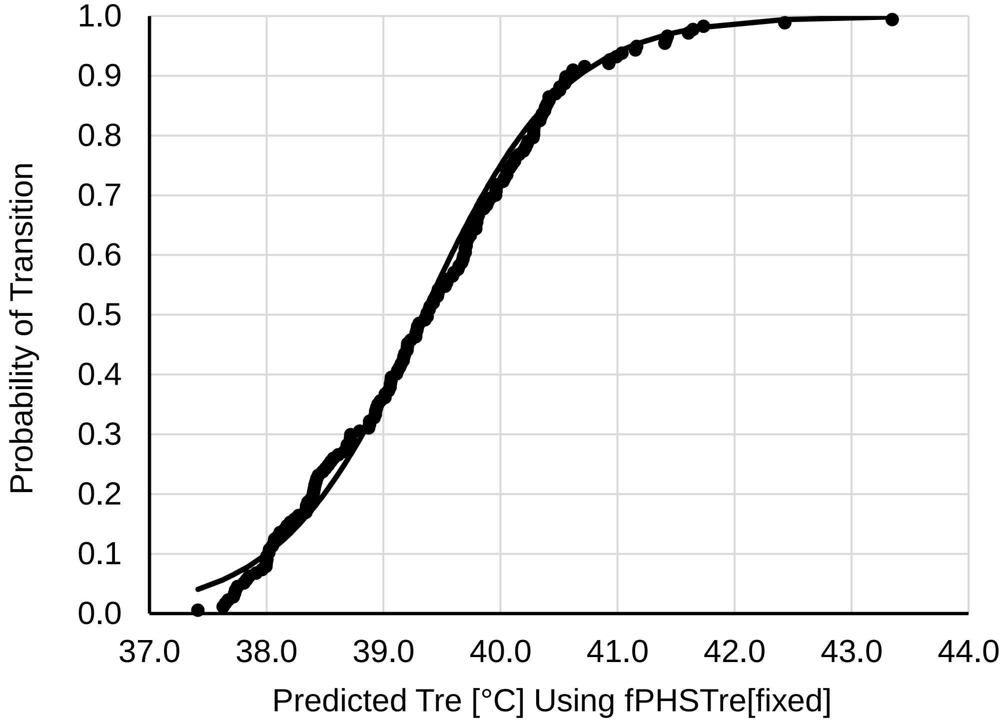

Figure 2. Probability of a limiting heat stress exposure for fixed personal data by predicted rectal temperature (Tre).

DISCUSSION

Predicted Heat Strain (PHS) was developed to address levels of heat stress in excess of the WBGT-based occupational exposure limits by introducing time as a fourth job risk factor. That is, it recognized that there can still be safe heat stress exposures above the WBGT-based limits if the exposure time is managed. For shorter periods of time, the heat stress would be limited by the increase in body core temperature reflected in a predicted rectal temperature. For longer durations, the limit may be due to dehydration. For the evaluation undertaken in this thesis, time-limited exposures to heat stress were undertaken at five levels of heat stress (HSL1 through HSL5) and three clothing ensembles (work clothes, water barrier coveralls and vapor barrier coveralls). Because PHS was designed to account for some personal factors such as height, body weight and initial rectal temperature, the PHS outcomes were examined using both the individual factors and fixed factors to represent an unknown population.

The original validation of PHS included only woven clothing that could be characterized as having a permeability index (i_m) of 0.38. Other investigators have modified the code to include other values for permeability. This study provided another opportunity to test the validity at high evaporative resistances. The ANOVA demonstrated that clothing and heat stress level were statistically significant along with interaction. Examining Figures 1 and 2 and the associated pair-wise comparisons using Tukey’s HSD demonstrated that the statistical significance was driven by a low predicted Tre for work clothes at the highest heat stress level. This observation supported the idea that adjusting i_m can account for the different evaporative resistances.

PHS recommends using a predicted Tre of 38°C as the decision threshold. This was validated by the PHS team who demonstrated that 95% of their observations were below 39.2°C and consequently the exposure would have a low probability of causing a heat stroke (Malchaire, et al, 2001). The criteria in this study was excessive physiological strain evidenced in a threshold rectal temperature or heart rate or with volitional fatigue. Using the PHS function adapted for this study, the relationship between the transition time from acceptable to unacceptable and predicted Tre was shown in Figure 3. For individual data, the 38°C threshold for predicted Tre was also protective of 95% of the trial exposures. This was a happy coincidence.

In occupational safety and health, the practitioner often does not have the luxury of personal data to consider in exposure assessment. The fixed values provide an opportunity to examine just job risk factors in the PHS model, and this was illustrated in Figure 4. There was a somewhat increased spread of the data from about 38°C at the lower limit to 41°C for the individual model and to 43°C for the fixed model. In addition, the threshold at 5% dropped from 38.0°C to around 37.8°C.

In conclusion, this thesis provided evidence that supported the use of PHS with a wide range of clothing. Further, the PHS model risk profile does not change when a fixed personal data are used; except that the predicted Tre threshold might be reduced to 37.8°C.

REFERENCES

American Industrial Hygiene Association. (2011*). The Occupational environment – Its evaluation, control and, management (3rd ed.).* D.H. Anna, (ed.) Fairfax, VA: AIHA.

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.

ISO, 2004. Standard No. 7933.

Jacklitsch, B., Williams, W.J., Musolin, K., Coca, A., Kim, J.-H., Turner, N., 2016. NIOSH criteria for a recommended standard: Occupational exposure to heat and hot environments. Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Cincinnati, OH.

Malchaire J. B.M (2006). Occupational heat stress assessment by the predicted heat strain model. *Industrial Health, 44.*

Malchaire, J., Kampmann B., Havenith, G., Mehnert P., & Gebhardt H.J.(2000). Criteria for estimating acceptable exposure times in hot working environments: a review.*Int Arch Occup Environ Health, 73*(4).

Malchaire, J. Piette, A., Kampmann, P., Mehnert, P. (2001). Development and Validation of the Predicted Heat Strain Model. *Ann Occp Hyg, 45*(2).

Plog, B.A., & Quinlan, P.J. (2012). *Fundamental of Industrial Hygiene (6th ed.)*. Itasca, IL: National Safety Council

Yunyan, A.J. & Rowlinson, S. (2014). Application of the predicted heat stain model in development of localized, threshold-based heat stress management guidelines for construction industry. *Annals Occupational Hygiene,58*(3). doi:10.1093/annhyg/met070

Wang, F., Kuklane, K., Gao, C. &, Holmer, I. (2011). Can the PHS model (ISO7933) predict reasonable thermophysiological responses while wearing protective clothing in hot environments? *Physical Measurements, 32:239*. doi:10.1088/0967-3334/32/2/007

APPENDIX A:

VISUAL BASIC CODE

Modified PHS Code with Function Returning a Value for Tre

The modification is a reduced set of input parameters and the predicted value for Tre at a specified time (Duration).

```
Function fPHSTre(Weight, Height, Tre0, Accl, Duration, Ta, Tg, Va, PvRH, M, Icl, imst)

' Predicted Heat Strain (PHS) model
' This is an adaptation of the code provided in ISO7933 (2017)
' The major change is that the code is called as a function rather than a subroutine
' Other changes include allowing for either RH or Pa to indicate humidity with PvRH;
' blank values are set to defaults; and initial Tre can be entered
' Further changes remove globe diameter, Drinking (assume that water is available),
' and the effects of direction of air velocity and walking are not considered.
' This function is used to test the USF time-limited data
' The function returns the value of Tre at Time = Duration
' Fixed Values from reducing the variable set

Drink = 1
Diam = 15
Work = 0
Posture = 1
defspeed = 0
Walksp = 0
defdir = 0

Dim Time As Integer

' EXPONENTIAL AVERAGING CONSTANTS
ConstTeq = Exp(-1 / 10): ' Core temperature as a function of M: time constant: 10 min
ConstTsk = Exp(-1 / 3): ' Skin Temperature: time constant: 3 min
ConstSW = Exp(-1 / 10): ' Sweat rate: time constant: 10 min
' INPUT OF THE MEAN CHARACTERISTICS OF THE SUBJECTS
```

```
' The user must make sure at this point in the programme that the following parameters are available.
' Standard values can be replaced by actual values.
If Weight = 0 Or IsEmpty(Weight) Then Weight = 75: ' Body mass kilogram
If Height = 0 Or IsEmpty(Height) Then Height = 1.8: ' Body height metres
If IsEmpty(Accl) Then Accl = 1: ' =1 if acclimatised subject, =0 otherwise
If IsEmpty(Drink) Then Drink = 1: ' Water replacement: =1 if the workers can drink freely, =0 otherwise

' COMPUTATION OF DERIVED PARAMETERS
Adu = 0.202 * Weight ^ 0.425 * Height ^ 0.725: ' Body surface area m2
aux = 3490 * Weight / Adu: ' Heat for 1°C increase of the body per m2 of body surface
SWmax = 400: If Accl = 1 Then SWmax = 500: ' Maximum evaporative capacity
wmax = 0.85: If Accl = 1 Then wmax = 1 ' Maximum wettedness
DMax = 0.05 * Weight * 1000: ' Maximum water loss in grams
If Drink = 0 Then DMax = 0.03 * Weight * 1000: ' if no free drinking

' INPUT OF THE PRIMARY PARAMETERS
' The user must make sure that, at this point in the program, the following parameters are available.
' In order for the user to test rapidly the program, the data for the first case
' in annex E of the ISO 7933 standard are introduced as default values.
If IsEmpty(Duration) Then Duration = 480: ' Duration of the work sequence in minutes
If IsEmpty(Ta) Then Ta = 40: ' Air temperature in degrees Celsius
If IsEmpty(Tg) Then Tg = Ta: ' Black globe temperature: °C
If IsEmpty(Diam) Then Diam = 15: ' Diameter of the black globe, in cm
If IsEmpty(Va) Then Va = 0.3: ' Air velocity metres per second
Tr = ((Tg + 273) ^ 4 + 1.1579 * 10 ^ 8 / 0.95 / (Diam / 100) ^ 0.4 * Va ^ 0.6 * (Tg - Ta)) ^ 0.25 – 273

' Parse out Pv and RH to find partial water vapour pressure kilopascals
If IsEmpty(PvRH) Then PvRH = 35 ' Relative humidity
If PvRH > 5.7 Then
RH = PvRH
Pa = 0.6105 * Exp(17.27 * Ta / (Ta + 237.3)) * RH / 100:
Else
Pa = PvRH
End If

If IsEmpty(M) Then M = 300: ' Metabolic rate, watts
Met = M / Adu: ' Metabolic rate, Watts per square metre
If IsEmpty(Work) Then Work = 0: ' Effective mechanical power watts per square metre

If IsEmpty(Icl) Then Icl = 0.5: ' Static thermal insulation clo
If IsEmpty(imst) Then imst = 0.38: ' Static moisture permeability index
' Effective radiating area of the body
```

```
Posture = 1: ' Posture = 1 standing, =2 sitting, =3 crouching
If Posture = 1 Then Ardu = 0.77
If Posture = 2 Then Ardu = 0.7
If Posture = 3 Then Ardu = 0.67
' Refective clothing
Ap = 0.54: ' Fraction of the body surface covered by the reflective clothing
Fr = 0.97: ' Emissivity of the reflective clothing (by default: Fr=0.97)

' Air motion displacements
defspeed = 0: ' =1 if walking speed entered, =0 otherwise
Walksp = 0: ' Walking speed, m/s
defdir = 0: ' =1 if walking direction entered, 0 otherwise
THETA = 0: ' Angle between walking direction and wind direction degrees

' CLOTHING INFLUENCE ON EXCHANGE COEFFICIENTS
Iclst = Icl * 0.155: ' Static clothing insulation
fcl = 1 + 0.3 * Icl: ' Clothing area factor
Iast = 0.111: ' Static boundary layer thermal insulation in quiet air
Itotst = Iclst + Iast / fcl: ' Total static insulation
' Relative velocities due to air velocity and movements
If defspeed > 0 Then
If defdir = 1 Then
Var = Abs(Va - Walksp * Cos(3.14159 * THETA / 180)): ' Unidirectional walking
Else
If Va < Walksp Then Var = Walksp Else Var = Va: 'Omni-directional walking
End If
Else
Walksp = 0.0052 * (Met - 58)
If Walksp > 0.7 Then Walksp = 0.7: 'Stationary or undefined speed
Var = Va
End If
' Dynamic clothing insulation
Vaux = Var: If Var > 3 Then Vaux = 3
Waux = Walksp: If Walksp > 1.5 Then Waux = 1.5
' Clothing insulation correction for wind (Var) and walking (Walksp)
CORcl = 1.044 * Exp((0.066 * Vaux - 0.398) * Vaux + (0.094 * Waux - 0.378) * Waux)
If CORcl > 1 Then CORcl = 1
CORia = Exp((0.047 * Var - 0.472) * Var + (0.117 * Waux - 0.342) * Waux)
If CORia > 1 Then CORia = 1
CORtot = CORcl
If Icl <= 0.6 Then CORtot = ((0.6 - Icl) * CORia + Icl * CORcl) / 0.6
Itotdyn = Itotst * CORtot
Iadyn = CORia * Iast
Icldyn = Itotdyn - Iadyn / fcl
' Dynamic evaporative resistance
' Correction for wind and walking
```

```
CORe = (2.6 * CORtot - 6.5) * CORtot + 4.9
imdyn = imst * CORe: If imdyn > 0.9 Then imdyn = 0.9
Rtdyn = Itotdyn / imdyn / 16.7

' INITIALISATION OF THE VARIABLES OF THE PROGRAMME
If IsEmpty(Tre0) Then Tre = 36.8 Else Tre = Tre0: ' Initial rectal temperature, °C
Tcr = Tre: ' Initial core temperature, °C, same as rectal temperature
Tsk = 34.1: ' Initial skin temperature, °C
Tcreq = 36.8: ' Initial core temperature associated with resting M, °C
TskTcrwg = 0.3 ' Initial skin – core weighting
SWp = 0: ' Initial sweat rate, W/m2
SWtot = 0: ' Initial total sweat rate, W/m2
Dlimtcr = 999: ' Duration limit of exposure due to increase in temperature, min
Dlimloss = 999: ' Duration limit of exposure due to excessive water loss, min

' ITERATION OF THE PROGRAMME
For Time = 1 To Duration
' Initialisation min per min: value at beginning of time i = final value at time (i-1)
Tre0 = Tre: Tcr0 = Tcr: Tsk0 = Tsk: Tcreq0 = Tcreq: TskTcrwg0 = TskTcrwg
' Equilibrium core temperature associated to the metabolic rate
Tcreqm = 0.0036 * Met + 36.6
' Core temperature at this minute, by exponential averaging
Tcreq = Tcreq0 * ConstTeq + Tcreqm * (1 - ConstTeq)
' Heat storage associated with this core temperature increase during the last minute
dStoreq = aux / 60 * (Tcreq - Tcreq0) * (1 - TskTcrwg0)
' SKIN TEMPERATURE PREDICTION
' Skin Temperature in equilibrium
' Clothed model
Tskeqcl = 12.165 + 0.02017 * Ta + 0.04361 * Tr + 0.19354 * Pa - 0.25315 * Va
Tskeqcl = Tskeqcl + 0.005346 * Met + 0.51274 * Tre
' Nude model
Tskeqnu = 7.191 + 0.064 * Ta + 0.061 * Tr + 0.198 * Pa - 0.348 * Va
Tskeqnu = Tskeqnu + 0.616 * Tre
' Value at this minute, as a function of the clothing insulation
If Icl >= 0.6 Then Tskeq = Tskeqcl: GoTo Tsk
If Icl <= 0.2 Then Tskeq = Tskeqnu: GoTo Tsk
' Interpolation between the values for clothed and nude subjects, if 0.2 < clo < 0.6
Tskeq = Tskeqnu + 2.5 * (Tskeqcl - Tskeqnu) * (Icl - 0.2)
' Skin Temperature at this minute, by exponential averaging
Tsk:
Tsk = Tsk0 * ConstTsk + Tskeq * (1 - ConstTsk)
If Time = 1 Then Tsk = Tskeq
' Saturated water vapour pressure at the surface of the skin
Psk = 0.6105 * Exp(17.27 * Tsk / (Tsk + 237.3))
' Mean temperature of the clothing: Tcl
Z = 3.5 + 5.2 * Var
```

```
If Var > 1 Then Z = 8.7 * Var ^ 0.6
auxR = 5.67E-08 * Ardu
FclR = (1 - Ap) * 0.97 + Ap * Fr
Tcl = Tr + 0.1
Tcl:
' Dynamic convection coefficient
Hcdyn = 2.38 * Abs(Tcl - Ta) ^ 0.25
If Z > Hcdyn Then Hcdyn = Z
' Radiation coefficient
HR = FclR * auxR * ((Tcl + 273) ^ 4 - (Tr + 273) ^ 4) / (Tcl - Tr)
Tcl1 = ((fcl * (Hcdyn * Ta + HR * Tr) + Tsk / Icldyn)) / (fcl * (Hcdyn + HR) + 1 / Icldyn)
If Abs(Tcl - Tcl1) > 0.001 Then Tcl = (Tcl + Tcl1) / 2: GoTo Tcl
' HEAT EXCHANGES
texp = 28.56 + 0.115 * Ta + 0.641 * Pa: ' temperature of the expired air
Cres = 0.001516 * Met * (texp - Ta): ' Heat exchanges through respiratory convection
Eres = 0.00127 * Met * (59.34 + 0.53 * Ta - 11.63 * Pa): ' through respiratory evaporation
Conv = fcl * Hcdyn * (Tcl - Ta): ' Heat exchanges through convection
Rad = fcl * HR * (Tcl - Tr): ' Heat exchange through radiation
Emax = (Psk - Pa) / Rtdyn: ' Maximum Evaporation Rate
Ereq = Met - dStoreq - Work - Cres - Eres - Conv - Rad: ' Required Evaporation Rate
' INTERPRETATION
wreq = Ereq / Emax: ' Required wettedness
' If no evaporation required: no sweat rate
If Ereq <= 0 Then Ereq = 0: SWreq = 0: GoTo SWp
' If evaporation is not possible, sweat rate is maximum
If Emax <= 0 Then Emax = 0: SWreq = SWmax: GoTo SWp
' If required wettedness greater than 1.7: sweat rate is maximum
If wreq >= 1.7 Then wreq = 1.7: SWreq = SWmax: GoTo SWp
Eveff = (1 - wreq ^ 2 / 2): ' Required evaporation efficiency
If wreq > 1 Then Eveff = (2 - wreq) ^ 2 / 2
SWreq = Ereq / Eveff: ' Required Sweat Rate
If SWreq > SWmax Then SWreq = SWmax: ' limited to the maximum evaporative capacity
SWp:
' Predicted Sweat Rate, by exponential averaging
SWp = SWp * ConstSW + SWreq * (1 - ConstSW)
If SWp <= 0 Then Ep = 0: SWp = 0: GoTo Storage
' Predicted Evaporation Rate
k = Emax / SWp
wp = 1
If k >= 0.5 Then wp = -k + Sqr(k * k + 2)
If wp > wmax Then wp = wmax
Ep = wp * Emax
' Heat Storage
Storage:
dStorage = Ereq - Ep + dStoreq
' PREDICTION OF THE CORE TEMPERATURE
```

```
Tcr1 = Tcr0
TskTcr:
' Skin - Core weighting
TskTcrwg = 0.3 - 0.09 * (Tcr1 - 36.8)
If TskTcrwg > 0.3 Then TskTcrwg = 0.3
If TskTcrwg < 0.1 Then TskTcrwg = 0.1
Tcr = dStorage / (aux / 60) + Tsk0 * TskTcrwg0 / 2 - Tsk * TskTcrwg / 2
Tcr = (Tcr + Tcr0 * (1 - TskTcrwg0 / 2)) / (1 - TskTcrwg / 2)
If Abs(Tcr - Tcr1) > 0.001 Then Tcr1 = (Tcr1 + Tcr) / 2: GoTo TskTcr
' PREDICTION OF THE RECTAL TEMPERATURE
Tre = Tre0 + (2 * Tcr - 1.962 * Tre0 - 1.31) / 9
' TOTAL WATER LOSS RATE AFTER THE MINUTE (in W / m2)
SWtot = SWtot + SWp + Eres: ' Total evaporation loss in watts per m2
SWtotg = SWtot * 2.67 * Adu / 1.8 / 60 ' Total water loss in grams

' COMPUTATION OF THE DURATION LIMIT OF EXPOSURE DLE IN MIN
' DLE for water loss, 95 % of the working population, in min
If Dlimloss = 999 And SWtotg >= DMax Then Dlimloss = Time
' DLE for heat storage, in min
If Dlimtcr = 999 And Tre >= 38 Then Dlimtcr = Time
' End of loop on duration
Next Time
fPHSTre = Tre
End Function
```