HEAT STRESS IN HOT UNDERGROUND MINES

by

Lucero Paloma Lazaro Trujillo

Copyright © Lucero Paloma Lazaro Trujillo 2020

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF MINING & GEOLOGICAL ENGINEERING

In Partial Fulfillment of the Requirements

For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

2020
THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

As members of the Dissertation Committee, we certify that we have read the dissertation prepared by: Lucero Paloma Lazaro Trujillo
titled: Heat stress in hot underground mines
and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

Moe Momayez
Date: Jun 4, 2020

Victor Octavio Tenorio
Date: Jun 5, 2020

Eric A Lutz
Date: Jun 7, 2020

Stephanie Griffin
Date: Jun 7, 2020

Final approval and acceptance of this dissertation is contingent upon the candidate’s submission of the final copies of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Moe Momayez
Date: Jun 4, 2020
Mining and Geological Engineering
ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and appreciation to Dr. Moe Momayez, my Ph.D. advisor, for his immense guidance and encouragement throughout these years. This dissertation would not have been possible without his support.

I would like to thank the committee members, Dr. Erick A. Lutz, Dr. Stephanie C. Griffin and Dr. Victor O. Tenorio Gutierrez for their support in completing this work.

I acknowledge the financial support provided by NIOSH under the award # 200-2014-59953 to the University of Arizona and the department of Mining and Geological Engineering.
DEDICATION

This Dissertation is dedicated to my husband, Jorge, and our children: Amelie and Alice, for their love and support.
To my parents, Nelson and Zonia, who have always been there.
And my mother and father in law, Irma and Jorge.
TABLE OF CONTENTS

Statement of originality............................................................................................................ 7

List of Figures .......................................................................................................................... 8

List of Tables ............................................................................................................................ 9

Abstract ..................................................................................................................................... 10

CHAPTER 1. INTRODUCTION ................................................................................................. 11

1.1. Scope of the problem........................................................................................................ 11

1.2. Heat indices ....................................................................................................................... 12

1.3. Predicted Heat Strain (PHS) [ISO 7933 (2004)]........................................................ 13

1.4. Real-Time thermometer-based capsule (VitalSense® Core Temp.)............................. 15

1.5. Study specific hypothesis............................................................................................... 15

1.6. Dissertation format......................................................................................................... 17

CHAPTER 2. CONCLUSIONS AND RECOMMENDATIONS .................................................. 21

2.1. Multi-factorial, evidence-based, and field-ready guidelines needed ......................... 21

2.2. Validation of the PHS .................................................................................................... 21

2.3. Effect of indoor/outdoor activities ................................................................................. 22

2.4. Modification of the PHS ............................................................................................... 22

2.5. Effect of perceived temperature .................................................................................... 22

2.6. Recommendations for future work and research ......................................................... 23
APPENDIX A – MANUSCRIPT 1 “Heat stress in hot underground mines: a brief literature review” Submitted for publication to the Mining, Metallurgy and Exploration Journal on May 2020


APPENDIX C – MANUSCRIPT 3 “Development of a Modified Predicted Heat Strain model for hot work environments” Published: 04 July 2020 in the International Journal of Mining Science and Technology

APPENDIX D – MANUSCRIPT 4 “The effects and perceptual responses of cooling technologies monitored during mining activity” Paper in progress
STATEMENT OF ORIGINALITY

I hereby declare that this Ph.D. dissertation is based upon original research, except when due reference is indicated in the text. This dissertation has not been submitted, in whole or part, for the fulfillment of any academic degree. The contribution to the knowledge I claim in the subject area of heat stress in mining are as follows:

1. A literature review in the subject area of heat stress in hot underground mines has been conducted by myself to understand state-of-the-art knowledge on the topic and to identify limitations and technical issues of current practices.

2. The application of the Predicted Heat Strain (PHS) index in hot mining environments and test its validity and reliability by comparison against a telemetry ingestible capsule (VitalSense).

3. The development of a new approach to relate thermal variables in order to modify and validate the original PHS index.

Lucero Paloma Lazaro Trujillo

University of Arizona, Tucson

May 2020
LIST OF FIGURES

Dissertation
Figure 1. Predicted Heat Strain (PHS) input/output data............................................. 14

Manuscript 1
Figure 1: Number of accidents in the mining industry (Surface and Underground) by level of experience: Beginner (0-1 year), Intermediate (1-5 years), Advanced (5-15 years) and Expert (>15 years). Data obtained from MSHA Forms 7000-1. .............................. 32
Figure 2: Number of heat-related accidents in the underground mining industry from 2010 until September 2019. Data obtained from MSHA Forms 7000-1. ................................. 33
Figure 3: Progression of heat stress symptoms over time ........................................... 38
Figure 4: Historical number of heat indices appeared over time ................................... 43
Figure 5: Heat acclimatization schedules ................................................................. 53

Manuscript 2
Figure 1. VitalSense core temperature (observed), PHS index temperature (Predicted) and Heart Rate vs time for the duration of the experiment................................................. 73
Figure 2. Bland-Altman plots of observed core temperature (VitalSense capsule) and predicted core temperature (PHS index), with means (solid line) and limits of agreement (dashed lines) ................................................................................................. 75
Figure 3. Descriptive statistics for total particulates: total diesel ..................................... 77

Manuscript 3
Figure 1. An example of an individual core temperature measurement........................... 92
Figure 2. VitalSense core temperature (observed) and PHS index temperature (predicted) over time for the entire time of experiments. ................................................................. 93
Figure 3. Bland-Altman plots of observed core temperature (VitalSense capsule) and predicted core temperature (modified PHS index), with means (solid line) and limits of agreement (dashed lines). ......................................................................................... 94

Manuscript 4
Figure 1: Distribution of the mining operators crew by activity .................................. 107
Figure 2: Subjective attributes and preference to wear a cooling vest .............................. 112
Figure 3: External temperature of the hardhat.............................................................. 115
LIST OF TABLES

Dissertation
Table 1. List of most accepted heat indices ................................................................. 12
Table 2. Pros/Cons of PHS application on related literature ........................................... 14

Manuscript 1
Table 1: Common heat Sources in Underground Mines .................................................. 39
Table 2: Heat Indices Applications in Mines ................................................................. 40

Manuscript 2
Table 1. Anthropometrical characteristics of all participants in the study ...................... 67
Table 2. Air temperature and Relative humidity averages at underground and surface levels ................................................................................................................................. 68
Table 3. Ratings by type of measurements across activities .......................................... 72

Manuscript 3
Table 1. Multiple linear regression results ...................................................................... 86
Table 2. Analysis of variance of multiple linear regression equation of core temperature Tcr with two independent variables, with no restrictions in the design.
\[ \Delta T_{cr} = 35.64 + 0.06902 \Delta T_{sk} - 82.61 \times \text{dStoreq/spHeat}. \] ................................................................................................................................. 87
Table 3. Mean and standard deviation of main parameters. ........................................... 88
Table 4. Core temperature means (°C) for the entire year and summer session; and Pearson and Kappa correlation coefficients between metrics based on modified PHS, VitalSense pill and PHS index models. ................................................................. 91

Manuscript 4
Table 1: Demographic data of the exposed operating crew ......................................... 109
Table 2: Results of Analysis of Variance (ANOVA) ......................................................... 113
Table 3: Rating of RPE, TS and PeSI ............................................................................... 114
Table 4: Comparison of Variation of RPE, TS, PeSI and PSA between different types of cooling vests ......................................................................................................................... 114
Table 5: Comparison of PCT between different types of cooling vests ...................... 115
ABSTRACT

This dissertation is focused on the assessment and prevention of heat-related illnesses in mineworkers due to excessive exposure to heat and humidity in hot environments. Heat stress is a serious environmental and occupational hazard. The damaging effects of heat stress can lead to major injuries such as heat stroke, heat exhaustion, or even death. Recent trends indicate no progress towards decreasing the heat-related accidents in the mining industry as reported by the U.S. Mine Safety and Health Administration, despite unquestionable advances in the area of mine safety in the last twenty years. Adherence to standardized heat indices that are appropriate in mining work-site environments is decidedly beneficial.

The purpose of the study was to: i) review of the current state of knowledge about heat stress and strain from published and specialized literature; ii) validate the Predicted Heat Strain (PHS) [ISO 7933 (2004)] model, one of the most scientifically robust index, through a comparison of the predicted core temperatures by the PHS model with a direct physiological measurement obtained from an ingestible telemetry pill (VitalSense capsule), and iii) improve the performance and accuracy of the PHS model by developing a new expression that relates core body temperature as a function of stored heat and skin temperature. Primary sources of data for the current study, including environmental and real-time physiological data, were collected from ten subjects performing typical mining activities at two underground mines located in Arizona.
CHAPTER 1

INTRODUCTION

1.1. Scope of the problem

The major hazard associated with high temperatures in surface and underground mines is the potential to impact the overall health and induce illnesses in mine workers. Depending on the nature and magnitude of heat and humidity exposure, disorders may vary from perceived thermal discomfort, fatigue, rash, heat exhaustion, heat cramps, heat syncope, heat stroke and death. Extreme temperatures may cause serious damage to a worker’s concentration and motor skills, increasing the risk for accidents.1 Naturally, the higher the ambient temperature, the higher the risk of experiencing heat strain. The American Conference of Governmental Industrial Hygienists (ACGIH) advised that workers should not be permitted to work when their internal body temperature exceeds 38°C, and when prolonged daily work is performed in hot environments.2

Hot environments where underground operations are conducted prevail in large parts of the Americas. Temperatures in the upper levels of the mine are still related to the air temperatures at the surface, whereas in deeper underground working areas, the temperature from the strata rise accordingly with the geothermal gradient. The same situation applies to humidity, which rises in the presence of hot underground water. Apart from the geothermal gradient, heat may also come from a variety of other sources in underground mines, including but not limited to auto compression, mechanized equipment, operating activities or electricity, etc., a situation that adds complexity to the problem.3,4,5,6

Of all the methods used to mitigate high temperatures and humidity in underground mines, ventilation and cooling systems are undoubtedly the best known and proven methods to reduce
heat in the environment. In the same line (reducing the heat in the environment), methods to control transmission of heat from different sources (strata, auto compression, etc.) have been of fundamental help and have reached high levels of technical development.\textsuperscript{3,4,7,8} However, while these systems efficiently control air temperatures in the environment, they are severely limited in identifying physiological abnormalities on mine workers. To address this problem, heat prediction models are required.

1.2. Heat indices

Heat Indices are thermal stress assessments or standards than individual mining companies may use on their own initiate. Heat indices have been largely validated in estimating labor’s risk against heat in other industries.\textsuperscript{9,10,11,12} There are many heat indices available, and given their low cost and relatively simple applicability, mining companies could use more than one index. Table 01 shows the most commonly used indices for underground mining.

\textit{Table 1. Most accepted heat indices}

<table>
<thead>
<tr>
<th>Heat Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Bulb Globe Temperature</td>
<td>Created in 1957. The most used widely index for underground mines because of its.\textsuperscript{13} Has been used in research to see the effect of the equipment, to evaluate mine workers physiological demands and hydration.\textsuperscript{14,15,16}</td>
</tr>
<tr>
<td>(WBGT)</td>
<td></td>
</tr>
<tr>
<td>Environmental Stress Index</td>
<td>Created in 2001 as an alternative to the WBGT under different climate conditions in Israel.\textsuperscript{17} Used for evaluation of heat stress to investigate correlation of ESI with physiological parameters in an open pit mine in Tehran, Iran\textsuperscript{18}</td>
</tr>
<tr>
<td>(ESI)</td>
<td></td>
</tr>
<tr>
<td>Predicted Heat Strain (PHS)</td>
<td>Created in 2001. The second most widely used index in mines. The PHS Index is based in the standard ISO 7933:2004: ergonomics of the thermal environment is used to evaluate heat stress in terms of high core temperatures or increasing water loss. PHS predicts the maximum</td>
</tr>
</tbody>
</table>
allowable exposure times. This index has been widely used in the mining industry (China, United States)\textsuperscript{10, 12, 19, 20}

<table>
<thead>
<tr>
<th>Thermal Work Limit (TWL)</th>
<th>Created in 2002. Widespread adoption in underground Australian mining. TWL has been proven to perform better than WBGT in outdoor work environments. \textsuperscript{21}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet-bulb dry temperature (WBDT)</td>
<td>Created in 2005 using the results of cumulative daily average WBGT index to detect heat stress risk. \textsuperscript{22}</td>
</tr>
</tbody>
</table>

1.3. Predicted Heat Strain (PHS) [ISO 7933 (2004)]

The Predicted Heat Strain (PHS) is a rational index derived from the heat balance equation and designed to assess the stress related to hot working conditions and determine maximum allowable exposure duration of an average individual. Based on rigorous mathematical formulations, it is generally agreed that the PHS is the most advanced of the thermal indices, improving the previous Required Sweat Rate (SWreq) [ISO 7933 (1989)] index. \textsuperscript{23, 24, 25} The PHS model was developed as a joint effort between eight European laboratories in the field of thermal factors which systematically reviewed the algorithms for calculating the physiological responses, concerning: the influence of respiratory heat losses, radiation on protective clothing, predicted mean skin temperature, exponential averaging of sweat rate and skin temperature, predicting core body and rectal temperature, distribution of the heat storage in the body and evaporative efficiency of sweating. \textsuperscript{26,27,28,29,30} Criteria to determine maximum sweat rates, maximum dehydration and maximum increased in core temperature was also based on the scientific literature and research of the time, although as stated by authors, the algorithms developed were subject to further study. \textsuperscript{24} Figure 1 shows the
anthropometric and environmental input data sets and PHS outcome. Table 2 summarizes pros/cons of PHS application based on related literature.

<table>
<thead>
<tr>
<th>I. Anthropometric</th>
<th>II. Environmental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>Duration (min)</td>
</tr>
<tr>
<td>Height</td>
<td>Air temperature (Ta)</td>
</tr>
<tr>
<td>Acclimated Y/N</td>
<td>Globe temperature (Tg)</td>
</tr>
<tr>
<td></td>
<td>Relative humidity (HR)</td>
</tr>
<tr>
<td></td>
<td>Air velocity (Va)</td>
</tr>
<tr>
<td></td>
<td>Metabolic rate (M)</td>
</tr>
<tr>
<td>III. Work rate/cloth</td>
<td>Diameter black globe (cm)</td>
</tr>
<tr>
<td>Metabolic rate</td>
<td>Initial central Temp. (°C)</td>
</tr>
<tr>
<td>Clothing insolation (Icl)</td>
<td>Drinking N/Y</td>
</tr>
<tr>
<td></td>
<td>Posture Stand/Sit/Crouch (1/2/3)</td>
</tr>
<tr>
<td></td>
<td>Walking Speed (0 if not walking) (km/h)</td>
</tr>
</tbody>
</table>

Figure 1. Predicted Heat Strain (PHS) input/output data

Table 2. Pros/Cons of PHS application on related literature

<table>
<thead>
<tr>
<th>Predicted Heat Strain (PHS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROS</td>
</tr>
<tr>
<td>- Internationally accepted heat stress index</td>
</tr>
<tr>
<td>- Can be measured with simple climatic instruments / Easily calculated from meteorological data / Limit values are based on physiological strain / Increase in core temperature and water loss / Work time calculated based on reaching limit criteria / Subsequent exposures can be analyzed for accumulated effects / Allows risk assessment. 31</td>
</tr>
<tr>
<td>- Evidence that supported the use of PHS with a wide range of clothing. 32</td>
</tr>
<tr>
<td>- Applies to all climates, normal clothing, and low to high activity. 31</td>
</tr>
<tr>
<td>- Useful to suggest protective limits for men at work in extremely hot environment. 33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Environmental parameters remain constant / it is applicable for very detailed assessment. 34</td>
</tr>
<tr>
<td>- PHS does not consider long exposures, e.g. whole workdays, when using average values for input parameters, e.g. metabolic rate. 35</td>
</tr>
<tr>
<td>- Over-predicted rectal temperatures, underestimated the thermal strain. 35</td>
</tr>
<tr>
<td>- Underestimation of rectal temperatures in PHS on critical ranges. 36</td>
</tr>
<tr>
<td>- Showed an unrealistic instantaneous decline followed by a steep increase when work stared again. 12</td>
</tr>
</tbody>
</table>
1.4. Real-Time thermometer-based capsule (VitalSense® Core Temp.)

The current study used the VitalSense Core Temperature capsule as valid and reliable technique to compare against the predicted values of the PHS index. The VitalSense is a real-time thermometer-based ingestible capsule that measures core temperature and transmits data in real time to a Sensor Electronic Module (SEM) wireless device. The VitalSense capsule is 8.6 mm in diameter, 23 mm in length and weights 1.6 grams with a temperature accuracy of ±0.1°C, over a range of 25°C to 50°C. Core temperatures and other vital signs such as skin temperature, heart rate, and respiration rate are measured and reported at a rate of four times per minute to the monitor. Several studies have supported the VitalSense capsule as a valid technique for heat stress assessment. 39,40,41,42

1.5. Study specific hypothesis

The purpose of this research was to synthesize existing peer-reviewed literature on heat stress assessments in hot underground mines, to validate the Predicted Heat Strain (PHS) index through a comparison with an ingestible telemetry system (VitalSense capsule) in a hot mining environment, and to propose a modification of the PHS index on one of its major assumptions (distribution of the heat storage in the body) and demonstrate that the modified algorithm improves predicting outcomes.
The hypotheses tested in this study are as follows:

1) Broadly adopted heat indices, industrial consensus, and field-ready guidelines for identifying – and predicting – physiological markers of heat strain are currently unavailable in the mining industry.

2) Certain mining activities are more exposed to thermal stress than others, depending on workload, intensity, and whether they are performed outdoors or indoors.

3) The Predicted Heat Strain (PHS) [ISO 7933 (2004)] has the potential to augment heat stress prediction and monitoring in the mining industry, but further study is required. Validity was determined by calculating t-test paired two samples for means, Pearson’s and Cohen’s Kappa comparing the results of the PHS with an established and highly accurate technology, the VitalSense telemetric ingestible capsule. It was hypothesized that results of two methods would correlate even better if the PHS model is able to adequately address environmental and industry-specific variables.

4) Direct-measured and derived independent heat strain variables such as skin temperature, heat stored in the human body, and personal factors (specific heat and body mass) predict measured or derived heat strain dependent variables such the core body temperature.

5) Predicted values of core body temperature (test variable) of the modified-PHS improved over the original PHS version

6) Using cooling devices of different technologies has a differential effect on the perceived temperature and comfort in hot mining environments
1.6. Dissertation format

The dissertation consists of four research manuscripts, which are included at the end of this document as appendices (Appendices A, B, C and D). The study attempts to contribute to the knowledge of predicting time limiting heat stress exposure of mine workers in hot underground mines. The following is a summary of the objectives and most relevant findings of each manuscript:

**Manuscript # 1 - “Heat stress in hot underground mines: a brief literature review”**

The first manuscript (Appendix A) is a literature review that summarizes the existing research and knowledge of heat indices applications in mining and identifies the potential of certain heat stress indices as a tool to aid the prevention of heat illnesses. This review of applications in the field, science, health and safety databases found that, since the first heat stress index appeared in 1905, more than 160 indices have been released in the literature. Researchers have been incorporating more and more thermal influencing variables to improve their predictive results, although only a few indices have been able to overcome their shortcomings and achieve acceptance from the mining industry, governmental agencies, and international organizations. This first manuscript addresses Hypothesis 1 by carrying out the specific work: Presenting a brief literature review of peer-reviewed research studies related to heat stress indices and gain insight on its reliability and applications in the industry.

**Manuscript # 2 - “Validation of the Predicted Heat Strain model in hot underground mines”**

The second manuscript (Appendix B) describes the application and validation of the Predicted Heat Strain (PHS) model. It was designed as a cross-sectional study using a sample of ten (10) male volunteer subjects, age 21.16 ± 1.85, weight 65.8 ± 4.5 kg, performing intensive tasks
where 8,143 pairs of core temperature data points were evaluated during hot and cool seasons of the year at two underground mines in Arizona. Environmental and physiological data was collected simultaneously to evaluate the core temperature results of the PHS and the VitalSense capsule. Predicted and measured data was analyzed using paired samples t-test statistical comparison, Bland-Altman method of measurement for multiple observations per subject, and Pearson’s correlation. Results indicated no statistically significant difference between the PHS index and the VitalSense (mean bias +0.014°C, 95% Confidence Interval: -0.010 to 0.038°C of core temperature readings), suggesting that both methods worked equally through all participant readings. However, results showed weak positive correlation (Pearson r=0.32), poor reliability on inter-class correlation and agreement. Also, results suggested that the PHS index ability to predict core temperatures increases in environments where the heat load is less such as those found underground.

The second manuscript addresses hypothesis 2 and 3 by carrying out the following work, respectively:

- Perform a descriptive analysis of heat stress responses on average mine workers performing typical mining activities in two hot underground mines in Arizona using the PHS index and VitalSense methods.

- Estimate correlation coefficients between the PHS index and the VitalSense capsule in a cross-sectional sample of ten underground mine workers in Arizona.

**Manuscript # 3** - “Development of a Modified Predicted Heat Strain model for hot work environments”
The third manuscript (Appendix C) investigates the influence of criteria-based assumptions for the determination of the PHS index. A modification of the original formulation regarding the distribution of heat on the body was developed. The modification is based on a new expression that relates the core temperature as a function of skin temperature and stored heat. It was found that the modified PHS (Mod-PHS) provides roughly 50% more accurate results than the original PHS index in terms of predicting core body temperature and improves statistical correlation and agreement.

The specific aims of manuscript # 3 to address hypothesis 4 and 5, respectively, are:
- Undertake a multiple linear regression analysis to develop a new expression that predicts the core temperature (dependent variable) of an individual performing an intermittent work as a function of the skin temperature and heat storage (independent variables) at time “t” (from 0 to 480 min).
- Development of a modified version of the PHS and application in the field. Validity of the modified-PHS and comparison with the original PHS index.

**Manuscript # 4** - “The effects and perceptual responses of cooling technologies monitored during mining activity”

The fourth manuscripts (Appendix D) studies and compares the influences of cooling technologies (cooling vests, evaporative cooling caps and sleeves) on the perceived temperature (a combined effect of air temperature, relative humidity, and speed of the air) of experienced miners working during the hottest time of their activities without disturbing their ordinary labor. Subjects gave ratings of perceived exertion (RPE), Thermal sensation (TS), and four other subjective properties. Activities tested in this study were held by pit geologists, pit maintenance
mechanics (planned maintenance and on-site overhaul), blasters (arrange and samplers), surveyors, and electricians. This manuscript tests Hypothesis 6.
CHAPTER 2

CONCLUSIONS AND RECOMMENDATIONS

2.1. Multi-factorial, evidence-based, and field-ready guidelines needed

Heat stress is a dangerous condition that can irreversibly affect the health, safety and productivity of mine workers. There have been many approaches to address the effects of heat stress on underground mine workers throughout history, from early ventilation planning using basic instruments to measure airflow and pressure drops, to the emergence of increasingly complex heat stress indices, and the more recent development of better legislative controls. Over the last century, heat stress indices have been incorporating more and more thermal influencing variables and increasing its accuracy on predicting human response to various thermal environments. However, due to a large number of available heat indices (more than 160) and the lack of a well-defined procedure and guidelines to select the most appropriate for a particular mining environment, only a few indices have been examined in the mining industry.

2.2. Validation of the PHS

A validation of the Predicted Heat Strain (PHS) was performed. The study assessed core temperatures provided by the PHS index and a core temperature pill (VitalSense) for ten acclimatized participants at two underground mines in Arizona. Multiple observations were made per individual and all core temperature measurements were taken on different days and during normal shift periods. Comparisons were made between real time experimental data and the PHS model. It was found that the PHS model showed no statistically significant difference with the VitalSense (mean bias +0.014°C, 95% CI: -0.010 to 0.038°C) core temperature readings. However, the PHS index tends to underestimate higher core temperature values.
2.3. Effect of indoor/outdoor activities

Data collected from indoor and outdoor activities provided a better representation of the daily work since they were both sources of loading and dissipating heat. In general, cooler environmental conditions were observed underground, especially during the summer, because the mine ventilation systems provided cooler air in the working areas. These results suggest that the PHS index ability to predict core temperatures increases in environments where the heat load is less such as those found underground.

2.4. Modification of the PHS

A modified-PHS model was developed to assess body core temperatures in hot work environments. The modification is based on a new expression that relates the core temperature as a function of skin temperature and stored heat. The modified PHS model was validated against telemetry pill system (VitalSense capsule) for core body temperature measurement and compared with the original PHS index. It was found that the modified PHS provides more accurate results than the original PHS index in terms of predicting core body temperature and improves statistical correlation and agreement. Another advantage of the modified-PHS method is that the proposed equation can be easily updated for any site-specific environment without the use of sophisticated coding techniques compared to the PHS index algorithms.

2.5. Effect of perceived temperature

Perceived thermal responses of mining workers are a valuable source of data that offers unique insight into the subject’s reaction to the implementation of new technologies (such as cooling
vest, evaporative hard hats or sleeves) or to any change applied to the heat stress management system.

2.6. Recommendations for future work and research

Although there have been many attempts to address the effects of heat stress on underground mine workers over the past decades, important questions remain unanswered. Estimating the effects of heat on subjects performing regular workload and regular eating and resting habits is extremely complex and involves multiple factors and processes, including subject’s behavioral patterns and fluctuations of environmental conditions. Future research work in the field of predicting and controlling heat stress in mining may include:

- Development of a centralized, user-friendly, and dynamic system to measure heat load along the underground works.
- Integrate thermal imaging technology for scanning occupational heat stress with predicted heat models of geological, physiological, and operating mechanisms.
- Investigate on the effects of behavioral variables that can significantly influence temperature and evaporation rates.
- Design experiments to study other influencing parameters such mine operation sizes, level of mechanization, workforce variability (age, gender, etc.)
- Investigate the effects of high confining pressure conditions in deep mining (typically at depths below 1,500 m) on core body temperature, and to a broader extent the effects of either soaring or freezing temperatures that would challenge future space exploration and mining. 43, 44
REFERENCES


APPENDICES

APPENDIX A – MANUSCRIPT 1
APPENDIX A - HEAT STRESS IN HOT UNDERGROUND MINES: A BRIEF LITERATURE REVIEW

Paloma Lazaro 1, Moe Momayez 1

1 Department of Mining, Geological & Geophysical Engineering, University of Arizona
1235 James E. Rogers Way, Tucson, AZ 85719 United States
E-mail: plazaro@email.arizona.edu; Tel. (720) 256-6850

Keywords: heat; hot environments; underground mines; heat stress; heat strain; heat stress indices.

Submitted for publication to the Mining, Metallurgy and Exploration Journal on May 2020
ABSTRACT

Interactions between human beings and their work environment require the body to regulate its temperature by balancing heat production and loss. Comfortable environmental conditions are crucial for keeping workers safe and healthy, and to maintain a suitable level of productivity. However, achieving a proper core body temperature may become challenging under different conditions, especially in high heat-generating workplaces such as hot underground mines. Because hot underground mines have the potential to expose workers to heat stress, compliance with standardized and regulated indices and criteria is distinctly required. The objective of this paper is to provide an overview of the current research on heat stress and strain in hot underground mines, collected from published and specialized literature. General definitions, statistics of heat-related accidents in mining, overview of the indices, standards, and recommendations for heat stress are provided herein.

1. INTRODUCTION

It only takes 1°C to break the body’s temperature balance and cause the heart, respiratory, and nervous systems to malfunction. Hot underground mines could severely impact mineworker health during a normal shift, as they may be exposed to heat from strata, auto-compression, machinery, work-related fatigue and other sources (Ryan A, Euler DS., 2017).

The fundamental requirement for the human body to function under normal conditions is to maintain the body’s core temperature within the range of 37°C ± 1°C. A constant
exchange of heat between the body and the environment is required to regulate the core
temperature (Jacklitsch et al., 2016). The heat exchange, however, is a complex and
dynamic process of thermoregulation between the body’s cells and their surroundings
mainly due to the thermal gradient (conduction), the transfer of heat through fluids (e.g.
blood) caused by molecular motion (convection), and other forms of exchange such as
radiation and evaporation on the skin surface. Therefore, the thermal and physiological
properties of the human cells and their production of metabolic heat will largely determine
the nature of the internal heat transfer, and hence, the body’s heat exchange. (Parsons, K.
C., 2003).

The National Institute for Occupational Safety and Health (NIOSH) recognizes that
workers in occupations such as mining, agriculture and construction are particularly
susceptible to death due to heat stroke. Frequently, these deaths are attributed to
“unacclimated workers.” Across all industries, 30 workers have died every year between
2003 and 2012 due to heat-related illnesses and injuries (OSHA 2008). In 2014 alone, 2,630
individuals suffered from heat exposure, which resulted in 18 deaths. The Occupational
Safety and Health Administration (OSHA) determines a “Hot Work Site” using a
combination of criteria including humidity, air temperature, wind speed, and radiation that
exceeds a wet bulb globe temperature of 26.1°C.

The Mine Safety and Health Administration (MSHA) reported that 717 heat-related
accidents, injuries and illnesses from 2010 to September 2019 (MSHA Data sets, 2019)
occurred in the mining industry including underground mines, quarries, open pits, strips
and mill operations and processing plants. The number of safety incidents per year suggests
that heat stress controls in the industry have come to a standstill, with no clear trend for improvement. Figure 1 tracks the number of accidents per year from 2000 and illustrates a breakdown of these accidents into four levels of experience. In underground mines, the conditions and patterns of these events bring to light other relevant factors such as season, type of activity, time of the day when accidents occurred, as well as statistics on environmental, equipment, acclimatization and heat from other activities (see Figure 2).

Figure 1. Number of accidents in the mining industry (Surface and Underground) by level of experience: Beginner (0-1 year), Intermediate (1-5 years), Advanced (5-15 years) and Expert (>15 years). Data obtained from MSHA Forms 7000-1.

Several attempts have been made by the scientific community, safety and health departments in mining companies, as well as national and international agencies to create heat stress standards and indices that integrate all the pertinent variables. However, a unified model for heat stress monitoring and prediction is yet to be achieved. Questions have been raised over the applicability of indices, how successful they are at preventing heat stress, and how they can be complemented to enhance performance. In this paper, a
review of recent publications on heat stress related illnesses and indices, as applicable to the mining industry, is conducted, in order to evaluate the state-of-the-art standards and practices.

2. DEFINITIONS

Heat storage and heat balance

Recent progress in the standardization of heat stress indices is founded on thermal concepts established early in the nineteenth century. In 1824, the French engineer and physicist, Nicolas Léonard Sadi Carnot, the "father of thermodynamics", postulated that the amount of work used to transport heat from a hot source to a colder one could also be
used to transport the energy back to a hot body. This principle ultimately became the basis for the first law of thermodynamics and applied to the assessment of heat stress. It states that energy cannot be created nor destroyed and that the balance of energy comes from the principle of conservation, according to:

\[ \text{Energy accumulated} = \text{Energy in} - \text{Energy out} \]  

\[ \text{Energy accumulated} = \text{Heat in} - \text{Heat out} \]  

‘Heat balance’ occurs in a body when the net accumulated energy equals zero (Epstein & Moran, 2006), thereby reaching a steady-state equilibrium between the body’s heat production and heat loss to the environment. The general equation of the human heat balance is expressed as follows:

\[ \text{Body Heat Storage} = S = M - (W + R + K + C + E + \text{Resp}) \ \text{(Wm}^2\ \text{units)} \]  

\[ S = \text{Metabolic rate} - (\text{Work} + \text{Conduction} + \text{Radiation} + \text{Convection} + \text{Evaporation} + \text{Respiration}) \]

The energy transferred by the metabolic rate (M) allows the body to do mechanical work (W), and the rest is liberated as heat (i.e. M−W). Heat exchange is defined as the dynamic transfer of heat between the body and the environment, and can be dissipated by radiation (R), conduction (K), convection (C), and evaporation (E). This heat exchange will be influenced by evaporation on the skin depending on factors such as humidity, air velocity and the combined effect of clothing and movement. Heat storage rate (S) is the sum of all the rates of heat production and heat losses (Havenith, G., 1999; Parsons, K. C., 1999, 2003). A positive heat storage value represents an increase of body temperature in a heating
system. Conversely, a negative heat storage value means that heat is lost under a cooling body temperature.

**Thermoregulation**

Human beings can self-regulate their body temperatures regardless of external influence, and so are considered homeothermic. Homeothermy is a thermoregulation property defined by a stable internal core body temperature that is often, though not necessarily, higher than the average environmental temperature (Marriott, 1993). Examples of thermoregulatory body reactions include sweating in hot environments and shivering in cold environments. It is easier for the human body to modify its temperature without wearing protective clothing, but if the body is limited by this condition, then the probability of experiencing heat strain rises (Bishop et al., 2014).

**Heat stress**

Heat stress is defined by NIOSH as “the net heat load to which a worker is exposed which results in an increase in heat storage in the body.” Sources of heat stress include metabolic heat, environmental factors, and clothing (Jacklitsch et al., 2016). Heat stress occurs when heat balance is no longer sustained, and the body cannot release additional heat to the environment by itself. In 1992, The American Conference of Governmental Industrial Hygienists (ACGIH) advised that workers should not be permitted to work when their internal body temperature exceeds 38°C in cases where prolonged daily work is performed in hot environments.
According on the ISO 7243 definition, a person that works in a hot environment is subjected to heat stress. More precisely, heat stress results from a combination of heat production by the body (physical activity), type of activities performed, and the environment, and the manner in which heat is transferred between the environment and the body.

Factors that can produce heat stress (Jacklitsch et al., 2016) include:

- Age: the older the person, the more susceptible
- Sex: women typically sweat less than men, making their core body temperature more likely to rise faster, especially if they are pregnant, increasing the probability of suffering from heat-related illnesses
- Percent body fat: higher percent body fat can lower blood flow and reduce the heat transfer from the skin to the environment
- Drug use (including therapeutic): will interfere with the thermoregulation process
- Alcohol use: must be prohibited prior to or during work because alcohol ingestion makes the human body intolerant to heat

**Heat strain**

NIOSH defines heat strain as “the physiological response to the heat load (external or internal) experienced by a person, in which the body attempts to increase heat loss to the environment in order to maintain a stable body temperature,” (Jacklitsch et al., 2016). According to this definition, “the physiological responses are dedicated to dissipating excess heat from the body” (ACGIH, 2015).
The severity of heat strain is affected by factors such as heart rate, core body temperature, oral temperature, skin temperature, water loss and body weight. Duration of exposure required to cause heat strain is variable for every person and depends on age, fitness, hydration, fatigue, drug or alcohol use, medications, and food intake (Donoghue, 2004; Xiang et al., 2014).

Heat strain is identified by various symptoms, including fatigue, nausea, dizziness and giddiness. The risk increases if a person is continuously sweating for hours, losing more than 3% of body weight, or exceeding 50 mmoles od sodium through urinary discharge in the 24-hour (Di Corleto, R. et al. 2003, 2014). The risk of heat strain in hot environments may be reduced by repetitive exposure because it enables workers to acclimatize, causing a reduction in heart rate and body temperature and an increase in sweating (Maté, J. & Oosthuizen, J. 2012).

**Heat disorders**

Workers that are exposed to high temperatures and are unable to regulate their core temperature could suffer from heat disorder, also known as heat illness. When the individual’s core temperature rises above a normal range, heat illness could follow. In one experiment involving nine males, tremors occurred when a temperature range of 36.33°C to 36.67°C was reached. Between 37.32°C and 37.68°C, abundant sweating occurred. If the core body temperature rises above 41°C, a person will experience physical duress such as trembling and sweating, and runs the risk of irreversible damage to tissues and cells. For temperatures over 43°C, the results could be catastrophic (Hunt, A. P. 2011). Figure 3 illustrates the progression of heat stress from minor to major over time.
The duration and magnitude of core temperature will determine the severity of heat illness. Hot work environments expose workers to a combination of factors including hot air temperatures, high humidity, wind speed, radiant heat load, metabolic demand, restrictive clothing, heat intolerance, fatigue, dehydration, and more. In such environments, unacclimated workers are at greater risk to experience heat strain. If work continues under the same conditions, workers may have heat-related injuries like heat cramps, heat syncope, heat exhaustion and finally a heat stroke when core body temperature exceeds 39°C. Some symptoms include lack of sweating, red, hot, and dry skin, increased heart rate, headache, dizziness, nausea and confusion. If left untreated, these symptoms can result in unconsciousness and possibly death (Brake & Bates, 1999).

**Heat sources**

In underground mines, heat may come from a variety of sources including, but not limited to the geothermal gradient, auto compression, mechanized equipment, and heat from...
activities and electricity (Maurya et al., 2015). Table 1 describes these common sources of heat in underground mine environments.

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geothermal gradient</td>
<td>Rate of increasing temperature with respect to increasing depth of the underground works. From 0 - 100m depth the increasing temperature is caused by atmospheric changes and groundwater. Below 100m depth the temperature is affected by tectonic activity and thermal rock characteristics.</td>
</tr>
<tr>
<td>Auto compression</td>
<td>Generated by compressed and heated air entering in the shaft as it flows downward</td>
</tr>
<tr>
<td>Mechanized equipment</td>
<td>Such as conveyors, shaft hoist and pumps</td>
</tr>
<tr>
<td>Heat from activities</td>
<td>Energy released as heat during drilling, blasting and welding operations</td>
</tr>
<tr>
<td>Electricity</td>
<td>The use of mechanical devices and electricity increase the heat load in the mine processes and light</td>
</tr>
</tbody>
</table>

3. GENERAL INDICES

**Historical overview**

Thermal stress assessments originated over 400 years ago, reaching one of its points of greatest progress with the introduction of the Wet Bulb Globe Temperature index in 1957. In the late 1500’s, the Italian physicist Galileo Galilei invented the first air thermometer. Then, around the year 1700, the first thermometric centigrade scale was devised, and the science of Thermometry was established (McPherson, R.K. 1962). However, it was not until 1905 when J.S. Haldane studied the effects of temperature and humidity of air on the body temperature under different circumstances of clothing, air currents and work. These experiments were conducted in the tin mines of Cornwall and resulted in the creation of
the wet bulb thermometer index to assess the severity of the work in thermal environments (Haldane, J.S. 1905). The kata thermometer was invented in 1914 by Hill and modified by Bedford and Warner in 1933 and used to measure air cooling power and, indirectly, small wind speeds in circulating air, by measuring the time taken for the temperature of the bulb of alcohol to make a specified drop – 100° to 95°F – (McPherson, R.K. 1962). In 1923, the effective temperature that produced the same degree of physiological strain was defined by authors Houghten and Yaglou in the research publication “Determining lines of equal comfort” (McPherson, R.K. 1962). In 1957, the most widely known index in the world was released, the Wet Bulb Globe Temperature index (WBGT) used by the United States Army to prevent fatalities due to heat stroke (Yaglou and Minard, 1957). From then on, a series of new indices came to light in the form of corrections or modifications of the above methods or as entirely new proposals. Table 2 summarizes the most used heat stress indices in the last century and their applications in the mining industry.

<table>
<thead>
<tr>
<th>Date</th>
<th>Index</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1916</td>
<td>Kata Thermometer (K)</td>
<td>Used in the gold mining industry in South Africa to express the cooling power of air (Lambrechts J. de V., 1972.)</td>
</tr>
<tr>
<td>1923</td>
<td>Effective Temperature (ET)</td>
<td>First used in South Africa. Further developed on the basis of subjective comparisons between climates by sedentary subjects. Widely used in the mining industry in Britain, Germany, Belgium and France (Graveling, R.A. et al, 1998).</td>
</tr>
<tr>
<td>1946</td>
<td>Corrected Effective Temperature (CET)</td>
<td>Invented by Vernon &amp; Warner, used the globe temperature instead of the dry-bulb temperature. Establishes the limits for work in a hot mine at Mount Isa, Queensland, Australia (Wyndham, C. H. et al, 1967).</td>
</tr>
<tr>
<td>1947</td>
<td>Predicted Four Hour Sweat Rate (P4SR)</td>
<td>Applied in hot underground mines in the tropics of northern Australia (Brake, D. J. and Bates G.P., 2003).</td>
</tr>
<tr>
<td>1957</td>
<td>Wet Bulb Globe Temperature (WBGT)</td>
<td>The most used widely index for underground mines because of its simplicity (Yaglou, C., &amp; Minard, D. 1957). Has been used in research to see the effect of the operating equipment,</td>
</tr>
<tr>
<td>Year</td>
<td>Method</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>--------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1957</td>
<td>Oxford index (WD)</td>
<td>The Oxford Index was invented in 1957 by Lind and Hellon and based on the wet bulb temperature (Tw) and dry bulb temperature (Ta). (Lind A., Hellon R., 1957) (Ongoma V., Muthama J.N., 2014). The Oxford index is not appropriate to use in cases where the radiation factor is important. Has been widely applied in mine rescue to calculate the tolerance time (Graveling, R.A. et al, 1998).</td>
</tr>
<tr>
<td>1971</td>
<td>New Effective Temperature (ET*)</td>
<td>Proposed by Gagge A. et al. (1971). Applicable over a wide range of climate situations, although too difficult to apply on a daily basis.</td>
</tr>
<tr>
<td>1971</td>
<td>Wet Globe Temperature (WGT)</td>
<td>Highly correlated with the WBGT for moderate heat and humidity conditions; however, this relationship is not constant for all environmental factors (Jacklitsch et al, 2016). Widely used in surface and underground mines.</td>
</tr>
<tr>
<td>1972</td>
<td>Basic Effective Temperature (BET) or ET(A)</td>
<td>More suitable for underground mine conditions. Largely used in the coal mining industry for longwall operations in Australia (Mitchell, P., 2003) and the United Kingdom and Europe in coal and potash mines (Hunt, A. P., 2011).</td>
</tr>
<tr>
<td>1979</td>
<td>Humidex</td>
<td>The humidex index was created in 1979 by the Atmospheric Environment Service of Canada to quantify the body sensations of a person in high temperature and humid conditions. Humidex has been used in hot open pit mines in Tehran Province, Iran. Studies show that Humidex is more valid than Effective Temperature (ET) and Discomfort Index (DI), is low-cost and user-friendly for interpretation (Nassiri P. et al, 2017). Also, Humidex performs better in hot conditions with humidity such as hot underground mines (Roghanchi P., Kocsis KC., 2017).</td>
</tr>
<tr>
<td>1996</td>
<td>Cumulative heat strain index (CHSI)</td>
<td>The first version of the Heat stress index (HIS) was released in 1955, applicable to standard workers (not using heavy clothing) and without high heat stress conditions (Belding &amp; Hatch, 1955). The HIS was corrected in 1966 by refining equations with exponents and coefficients (McKarns J.S. &amp; Brief R.S., 1966). The HSI monograph simplifies the use of the index analyzing the heat stress factors (Jacklitsch et al.,</td>
</tr>
<tr>
<td>Year</td>
<td>Index Name</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1905</td>
<td>HSI</td>
<td>The HSI index was used in mines in Tehran, Iran (Nassiri P. et al, 2017). The CHSI appeared in 1996, as an assessment to predict the heat strain during heat exercise test in terms of core temperature and heat rate (Frank A. et al, 1996).</td>
</tr>
<tr>
<td>1996</td>
<td>CHSI</td>
<td>The CHSI appeared in 1996, as an assessment to predict the heat strain during heat exercise test in terms of core temperature and heat rate (Frank A. et al, 1996).</td>
</tr>
<tr>
<td>1998</td>
<td>Modified discomfort index (MDI)</td>
<td>The MDI is a simple tool to measure the heat load (Thom E. C., 1959) and can replace the WBGT at certain latitudes (Moran D.S. et al, 1998). MDI is applied in the control of Australian Bushfires, ensuring a safe environment in the shelters (Haberley, B., 2013).</td>
</tr>
<tr>
<td>2001</td>
<td>Predicted Heat Strain (PHS)</td>
<td>The second most widely used index in mines, the PHS Index is based in the standard ISO 7933:2004: ergonomics of the thermal environment is used to evaluate heat stress in terms of high core temperatures or increasing water loss. PHS predicts the maximum allowable exposure times. This index has been used in China’s coal mining industry to study the heat stress in miners in a movable refuge chamber (Hao, X. et al, 2016), and studies of miners using shorts and normal mining clothing in hot underground coal mines in China (Jiansong Wu, et al, 2016).</td>
</tr>
<tr>
<td>2001</td>
<td>Environmental Stress Index (ESI)</td>
<td>The ESI was developed as an alternative to the WBGT under different climate conditions in Israel (Moran D.S. et al, 2001). Used for evaluation of heat stress to investigate correlation of ESI with physiological parameters in an open pit mine in Tehran, Iran (Jafari M.J. et al, 2016).</td>
</tr>
<tr>
<td>2002</td>
<td>Thermal Work Limit (TWL)</td>
<td>Widespread adoption in underground Australian mining. TWL has been proven to perform better than WBGT in outdoor work environments (Miller V.S., Bates G.P., 2007).</td>
</tr>
<tr>
<td>2005</td>
<td>Wet-bulb dry temperature (WBDT)</td>
<td>Created in 2005 using the results of cumulative daily average WBGT index to detect heat stress risk (Wallace, Kriebel, Pennett, et al., 2005).</td>
</tr>
<tr>
<td>2012</td>
<td>Universal Thermal Climate Index (UTCI)</td>
<td>The UTCI was established by the International Society of Biometeorology (Weihls P., et al, 2011). This index has been well-accepted in the industry because it more precisely represents human biothermal conditions (Blazejczyk et al. 2012). The UTCI index has been used in mines in Tehran, Iran (Nassiri P. et al, 2017).</td>
</tr>
</tbody>
</table>

From the earliest research studies of Haldane and the publication of his index in 1905, the number of heat-measuring indices increased over the following decades, reaching a higher frequency of publications in the second half of the twentieth century. Figure 4 illustrates a
historical view of the 167 heat indices highlighting the most distinguishing characteristic of each period.

**Figure 4.** Historical number of heat indices appeared over time

**Categories of heat stress indices**

Several attempts have been made to create indices that describe and measure the properties of heat stress. Consequently, these indices can be used to define methods for assessment, recognition, prediction and control of human responses to heat stress. The many heat stress indices available can be conveniently grouped into three types: rational, empirical, and direct (Brake & Bates, 2002; Epstein & Moran, 2006).

**Rational:** Rational indices are based on the calculations of the heat exchange between behavioral and environmental variables, and are characterized by being more exhaustive. They predict the human responses such as sweat rate and core body temperature increases. Examples of rational indices include The Operative Temperature Index (OT), Heat Strain Index (HSI), and Predicted Heat Strain (PHS).
**Empirical**: Empirical indices utilize measurements of environment-induced physiological strain using standardized instruments. Empirical indices use human responses to exercises that are performed under different monitoring conditions. These responses are catalogued in databases, models or nomograms. The Predicted Four-Hour Sweat Rate index (P4SR) is an example of an empirical index.

**Direct**: Direct indices are based on direct measurements of environmental variables using user-friendly equipment. Examples of direct indices include the Effective Temperature Index (ET), Corrected Effective Temperature (CET), Wet-Bulb Globe Temperature (WBGT), Discomfort Index (DI), Oxford Index (WD), Fighter Index of Thermal Stress (FITS), Modified Discomfort Index (MDI), and Wet-Bulb Dry Temperature (WBDT).

4. COMMONLY USED INDICES FOR UNDERGROUND MINING

**Globe Thermometer Temperature (Tg)**

Since the invention of the black-globe thermometer in 1930, the globe temperature (Tg) has been regarded as the value that most appropriately integrates the effects of the radiation factor. For that reason, Tg has been given significant weight, determined by experiment, in the WBGT Index formula to account for radiation (i.e. 30% for indoors conditions and 20% for outdoors with solar radiation). Additionally, Tg is the main variable in calculating the Mean Radiant Temperature, substituting in importance for the dry-bulk temperature (McPherson, R.K. 1962). In fact, the black-globe thermometer was devised after realizing that the wall and floor temperatures of the experiment room never reached the temperature of the air (Ta) inside, and that for the experiment purposes, a new device
was required to sum up the sources of radiation in a given area (Vernon, H.M. & Warner, C.G., 1932). The black globe thermometer consists of a 150 mm (6 inch) copper black globe with an ordinary thermometer located at the center. After 80 years, it is still the more widely used thermometer to assess the effects of radiant and convective heat transfer on humans and animals (Purswell, J. L. & J. D. Davis, 2008). One disadvantage, however, is that in situations of considerable range of air velocity, the black-globe thermometer gives a false impression of warmth of the environment (Aparicio, P. et al., 2016).

**Wet-Bulb Globe Temperature (WBGT)**

WBGT, an empirical heat stress index, is the most commonly-used index to manage occupational heat stress. Invented in 1957 by Yaglou and Minard for the US Navy, WBGT was used to control heat stress during military training to prevent heat illness. WBGT is standardized by NIOSH and the International Organization for Standardization as ISO 7243.

The Wet-Bulb Globe Temperature is calculated using the following equations:

For indoors or outdoors without direct sun exposure:

\[ WBGT = 0.7Tw + 0.3Tg \]  \hspace{1cm} [4]

For outdoors with direct sun exposure:

\[ WBGT = 0.7Tw + 0.2Tg + 0.1Ta \]  \hspace{1cm} [5]

Where \( Tw \) is the natural wet bulb temperature [°C], \( Tg \) is globe temperature [°C] and \( Ta \) is air temperature [°C].
WBGT is easy to use and therefore widely accepted in the industry to measure heat stress in humans and animals. WBGT takes into account environmental conditions including air temperature, air movement speed, radiant heat, solar radiation on humans, and body cooling. However, WBGT is limited by not considering the metabolic rate, air movement and the wind speed effect.

**Required Sweat Rate (S\textsubscript{req})**

The Required Sweat Rate is a rational and complex index based on the heat balance equation. It was developed in 1981 by Vogt et al in the laboratories of Strasbourg, France as part of a research project program sponsored by the (ECSC) European Coal and Steel Community. The model was validated using data from 50 field studies and 60 laboratory experiments. The environmental variables involved were air temperature, humidity, air velocity, radiation and metabolic rate. (Malchaire, J., 1991).

Index outputs are mean skin temperature, maximum evaporation rate, required evaporation rate and Required Sweat Rate. To calculate the Required Sweat Rate, it is necessary to estimate the heat exchange between the human body and its environment for maintaining thermal homeostasis. Other factors involved are the time weighted means of required (E\textsubscript{req}) and maximal (E\textsubscript{max}) evaporation rates, though these factors will only be reliable if the relationship between physical stress and sweat rate is linear (Malchaire, J., 1991).

**Predicted Heat Strain (PHS)**

In 2005, the Predicted Heat Strain (PHS) came out as a rational index after a new revision of ISO 7933. The PHS updates and improves upon the Required Sweat Rate index in the following aspects (Malchaire, J. et al., 2001):
a. New method of determining heat loss: respiratory evaporative (Ere) and convective (Cres)
b. New algorithms that predict heat exchanges (including consideration of normal and special reflective clothing)
c. The influence of radiation in protective clothing
d. Determination of mean skin temperature (for nude and clothed subjects)
e. Exponential averaging to calculate the skin temperature and sweat rate
f. Prediction of mean body temperature (skin and core weighting)
g. Determination of core temperature (factoring in heat storage distribution in the body)
h. Determination of the rectal temperature limited to 38.0°C (using mean core temperature)
i. Evaporation efficiency of sweating depending on the level of humidity
j. The core temperature and metabolic rate as directly proportional variables
k. Maximum wetness for non-acclimatized subjects
l. Estimation of the maximum sweat rate (for acclimatized and unacclimatized subjects)
m. Maximum water loss of 7.5% of body mass for an average subject

A significant amount of resources were devoted to validate this PHS Model. Results from many field experiments under hot conditions and 909 laboratory studies were collected to build a rigorous database by Malchaire and a team of European researchers in the nineties. The PHS predicts minute by minute physiological responses including skin temperature, core temperature, and sweat rate, and is able to give the maximum allowable exposure duration at any time and condition. In addition, the PHS predicts heat strain in terms of
dehydration and increased core temperature limits - both critical parameters associated with productivity losses.

**Thermal Work Limit (TWL)**

The Thermal Work Limit is a rational index based on the thermal balance equation. TWL has been more extensively applied in underground mines than the Wet Bulb Globe Temperature (WBGT) because of its reliability (Miller & Bates, 2007). TWL is defined by the maximum metabolic rate that a hydrated and acclimatized individual could maintain. The core body temperature and the sweat rate should be < 38.2 °C and < 1.2 kg per hour respectively. The TWL requires them to be proactive, taking measurements the moment they feel the workload exceeds the limits. (Brake & Bates, 2002; Di Corleto, R. et al. 2014).

**Effective Temperature (ET)**

The effective temperature is an empirical index of heat exposure developed to help determine the effects of temperature and humidity on human comfort (Parsons, K. C., 2003, 2006). The ET index was created by Houghton and Yaglou from The American Society of Heating and Ventilating Engineers (ASHVE) in 1923. ET uses the physiological responses from data collected at different climatic conditions. The technique consisted of exposing three subjects to two rooms at different temperatures and letting them judge which one was warmer. As a result of this experiment, two psychometric charts were developed: one for a subject dressed in normal American-style clothing, the other the naked to the waist. The limitations of this index are the use of subjective criteria of the sample, in this case men seated at rest with the mindset that an average eastern American male possess (Lee, D.H.K., 1980). Later, after ET nomograms and calculations were modified, the substitution of the
dry-bulb temperature for the globe temperature by Vernon and Warner in 1932 will help to determine the radiation levels; this index became then becomes the corrected effective temperature (CET) (Parsons, K. C., 2003, Blazejczyk, K., 2012).

**Wet Globe Temperature (WGT)**

The Wet Globe Temperature (WGT) is an empirical heat stress index commonly used in the steel industry and has been applied in many physical models. The WGT uses a Black Globe Temperature Sensor, has a form of a botsball (2.5-inch diameter black globe covered with a damp black cloth), and includes a black globe with a thermometer inserted in the center. The reading should be taken after 10–15 minutes of exposure once temperature has stabilized. One disadvantage of this method is that the Black Globe Temperature Sensor can be expensive (Dimiceli, V. et al., 2011). Additionally, the measurement is affected by dry and evaporative heat transfer, as a sweating human would be, and its application requires special skills and experience to use it as a heat stress index (Parsons K.C., 2003).

5. INTERNATIONAL STANDARDS AND RECOMMENDATIONS FOR U.S. UNDERGROUND MINES

**ISO Standards**

The International Organization for Standardization (ISO) has developed human thermal assessment methodologies for hot, moderate and cold environments. For hot environment exposure, the following standards apply:


c. ISO 8996: Ergonomics of the thermal environment - determination of metabolic rate.

d. ISO 9886: Ergonomics - evaluation of thermal strain by physiological measurements.

e. ISO 9920: Ergonomics of the thermal environment - estimation of thermal insulation and water vapor resistance of a clothing ensemble.

**NIOSH and ACGIH standards**

The National Institute for Occupational Safety and Health (NIOSH) and the American Conference of Governmental Industrial Hygienists (ACGIH) established guidelines that seek to control heat strain and stress by limiting the time spent working in a hot environment. The NIOSH criteria document “*Recommendations for an Occupational Standard for Workers Exposed to Heat and Hot Environments*” (Jacklitsch et al., 2016) outlines the following limits:

a. The NIOSH Recommended Exposure Limits (RELs): developed to “protect most healthy workers” (physically and medically fit, wearing appropriate clothing) exposed to environmental and metabolic rate (M in Watts) from developing adverse heat-related health effects.

\[ REL [^°C-WBGT] = 56.7 - 11.5 \log_{10} M \]  \[6\]

b. The NIOSH Recommended Alert Limits (RALs): for unacclimated workers.

\[ RAL [^°C-WBGT] = 59.9 - 14.1 \log_{10} M \]  \[7\]

The NIOSH WBGT limits are similar to those of other national and international standards (Jacklitsch et al., 2016).
ACGIH is an organization that publishes occupational exposure limits in terms of core body temperature. ACGIH has developed a system with which the heat stress for a certain work task may be determined based on a time-weighted average (TWA), WBGT, and metabolic rate:

a. **Threshold Limit Value (TLV):** protective of almost all acclimatized, adequately hydrated, unmedicated, healthy workers.
b. **Action Level (AL):** protective of unacclimatized workers and represents exposures for which management should consider implementing a heat stress management program.

According to ACGIH, the TLV associated with loss of judgment and reaction time is when core body temperature is maintained at less than 38.0°C (ACGIH, 2015). Physical strain is present when core temperature is 38.6°C and above. If left untreated, the strain can progress to acute heat illness and eventually a heat stroke (Varley, F., 2004).

**MSHA & OHSA standards**

The Mine Safety and Health Administration (MSHA) defines a hot worksite as any environmental conditions that raises the WBGT to 26°C or higher. MSHA proposes acclimatization schedules for new mining employees and those returning to work after nine or more consecutive days leave. Neither MSHA nor OSHA has set exhaustive regulatory limits for heat exposure to miners. OSHA has, however, recommended limits for preventing heat strain:

a. Every person exposed to extraordinarily hot conditions should be individually monitored. These conditions occur at temperatures greater than 21°C or when the
metabolic load exceeds 500 kcal/hour. OSHA recommends monitoring oral temperature, heart rate and body water loss.

b. Oral temperatures should be taken after work hours but before the employee drinks water. It can be measure with a clinical thermometer and should not exceed 37.6 °C.

c. Heart rates should be measured at the beginning of the resting period. Measure the radial pulse for thirty seconds, and it should not exceed 110 bpm. Otherwise, the next work period should be shortened by one third of the time.

d. Body water loss is performed by weighing the employee at the beginning and end of the working day. If the weight loss is 1.5% of the total body weighting, the employee should increase fluid intake.

**Acclimatization (MSHA & NIOSH)**

New operators are at highest risk for heat illness, making acclimatization schedules are a critical part of any onboarding program. The following are the acclimatization schedules for acclimatized (workers with previous experience in hot working environments) and unacclimatized workers (new workers in extreme heat) according to MSHA and NIOSH:
According to Fig. 5, NIOSH’s acclimatization schedule is more preventive and gradual than MSHA’s, because MSHA recommends immediately exposing new workers to 50% of their shift in a hot environment, thus increasing the probabilities of heat stress. If the worker is dehydrated, sick, or taking medication, they will not be able to adapt, even with gradual acclimatization.
The American Industrial Hygiene Association (AIHA) set exposure limits including WBGT recommendations, time-weighted averages, NIOSH recommendations, ACGIH TLVs®, and ISO recommendations in their 2003 publication, “The Occupational Environment: Its Evaluation, Control, and Management”. AIHA concludes that the WBGT threshold values are basically equivalent (Jacklitsch et al., 2016).

6. CONCLUSION

There have been many approaches to assess the effects of heat stress on underground mine workers throughout history, from early ventilation planning using basic instruments to measure airflow and pressure drops, to the emergence of increasingly complex heat stress indices, and the more recent development of better legislative controls. Over the last century, heat stress indices have been incorporating more and more thermal influencing variables to improve their predictive results. Since the first heat stress index appeared in 1905, more than 160 indices have been inventoried in the literature, although only a few have been able to overcome their shortcomings and have achieved acceptance from the mining industry, governmental agencies, and international organizations.

Among the most commonly accepted heat stress indices in the industry are the Wet Bulb Globe Temperature (WBGT), the Predicted Heat Strain (PHS) and the Thermal Work Limit (TWL). The WBGT is the most widely used index to assess heat stress; WBGT has played a considerable role in the prevention of heat illness due to its controls and simplicity of use, though it has limitations including the omission of clothing effects, activity types, and behavioral factors. On the other hand, The Predicted Heat Strain (PHS) index considers
both environmental and behavioral factors in hot workplaces and is able to predict the potential water loss in addition to the core temperature and provide an estimate of the duration of exposure limits. The PHS is an exhaustive and complex heat strain index that can report the physiological response of a group rather than an individual. This index also has user-friendly applications to identify the heat stress such as the “Heat Stress Risk Phone App” for non-expert users. Finally, the third most commonly used index in mining is the Thermal Work Limit (TWL), which provides the maximum metabolic rate allowable and also offers a work-rest regime.

Research on heat stress conducted in the last few decades has been focused on integrating behavioral and activity workload factors with environmental factors. Behavioral factors include metabolic rate and clothing (insulation and moisture permeability characteristics), while environmental factors include the ambient and radiant temperature, humidity, and air movement (Epstein, Y. & Moran, D., 2006). In hot environments, humans adapt with behavioral responses beginning with the vaporization of sweat on the skin to conserve the heat balance, and can be classified as voluntary, semi-voluntary, and involuntary thermoregulatory responses (Pisacane, V. et al., 2007). Voluntary behavioral acts include: activating a ventilation device, leaving the hot environment, changing clothing, drinking water, resting in the shade, using a cooling vest or other sorts of protective equipment. In terms of the activity workload, acclimatization has been considered as an effective way of adapting new workers to hot workplaces.

Notwithstanding a wide range of theories and published research on heat stress indices and the enormous progress made in providing underground miners with safer thermal
conditions, heat-related accidents continue to occur in the industry, as reported by the Mine Safety and Health Administration (MSHA) accidents injuries data sets. Moreover, there has been no visible improvement in the reduction of accidents in the fifteen last years, which leads us to conclude that the heat stress control policies could be directed to finally integrate all the possible variables in the measures of heat and to seek its optimum applicability to heat stress management.

Conflict of Interest The authors declare that there is no conflict of interest.

REFERENCES

1. ACGIH, 2015, TLVs and BEIs: threshold limit values for chemical substances and physical agents and biological exposure indices, Cincinnati, OH: American Conference of Governmental Industrial Hygienists.


29. Jiansong Wu, Weiqi Guo, Ming Fu. Heat stress evaluation of miners wearing shorts or normal mining ensemble at the working face in hot coal mines using the Predicted Heat Strain model. 11th International Meeting on Thermal Manikins and Modeling(11i3m), Suzhou, China, Oct. 12-14, 2016.


APPENDIX B – MANUSCRIPT 2
APPENDIX B - VALIDATION OF THE PREDICTED HEAT STRAIN MODEL IN HOT UNDERGROUND MINES

Paloma Lazaro 1, Moe Momayez 1

1 Department of Mining, Geological & Geophysical Engineering, University of Arizona
1235 James E. Rogers Way, Tucson, AZ 85719 United States
E-mail: plazaro@email.arizona.edu; Tel. (720) 256-6850

Keywords: Predicted heat strain, hot underground mines, heat strain, heat stress

Published: 27 June 2019 in the Mining, Metallurgy and Exploration Journal 2019; 36(6):
1213-1219
ABSTRACT

Heat-Related Illnesses (HRI) are relatively common in both hot surface and underground mining operations. When workers are exposed to extreme heat or strenuous work in a hot environment, they become prone to heat stress. Heat strain is the result of the body’s response to external and internal heat stress. It is therefore vital for the conditions leading to heat strain be detected and treated in a timely manner. Heat-related illnesses are manifested by exhaustion and heat stroke. The Predicted Heat Strain (PHS) [ISO 7933 (2004)] model has been developed to predict the health condition of the worker in terms of core body temperature and water loss. The PHS Model tested in this study is based on eight physical parameters that are measured at different intervals during a work shift. They include air temperature, humidity, radiation, air velocity, metabolic rate, clothing insulation, posture and acclimatization. The model predictions are then compared with a direct physiological measurement, such as core body temperature. We present the results of an extensive study that monitored and predicted body’s response to heat stress under different environmental and working conditions. The PHS model provided reliable results in most instances in comparison to other prediction methods currently in use in the field.

1. INTRODUCTION

A large number of underground mining occupations are characterized by physically demanding activities generally take place in harsh working environments. Mineworkers are typically exposed to heat and physical exertion that can result in Heat-Related Illnesses (HRI) such as heat cramps, heat syncope (fainting), heat exhaustion, and heat stroke. Several other sources of heat in underground mines have been identified that increase the incidence of heat-related illnesses among the mining workforce, including geothermal
gradient (increasing rock temperature with depth), seasonal climate, auto-compression, mining methods, groundwater, diesel equipment liberated heat, blasting, human metabolism among others [1,4,13]. The implementation of mine ventilation and cooling systems is the primary means of providing a comfortable working environment. However, the adoption of heat stress indices and models that predict the physiological response of human body in hot conditions will significantly reduce the risk of heat strain/stress by allowing intervention prior to advanced heat related illness or exhaustion. One of the most accepted indices to evaluate the potential for thermal stress is the Predicted Heat Strain (PHS), which has become the main driver for establishing heat management guidelines in the military, construction, sports and other industries [18].

The Predicted Heat Strain (PHS) [ISO 7933 (2004)] is a rational index derived from the thermal balance equation. Since its formulation in 2004 to improve the previous Required Sweat Rate (SWreq) [ISO 7933 (1989)] index, the PHS index allows for in-depth analysis of physical work environments to quantify and predict physiological parameters of an average individual in terms of core, skin and rectal temperatures, and the sweat rate in a minute-by-minute basis. The PHS index project brought together researchers from laboratories in eight European research centers in the field of thermal physiology [14], and finally replaced the previous SWreq version by addressing limitations that were observed for more than a decade with respect to its applicability. The PHS index project developed an integral approach towards the evaluation and prevention of the risks associated with thermal environment by concentrating on important specific aspects such as the influence of various clothing sets on the evaporation and convection heat transfer, the distribution of heat temperatures in the human body and its relation to several primary climatic
parameters, and the definition of limit criteria for sweat rate, dehydration and maximum core temperatures. The calibration of the PHS model was performed using algorithms selected from the most recent scientific literature, and was subsequently validated by a large data set obtained from laboratory and field experiments (672 and 237 sets of data respectively) conducted by the eight partner laboratories [14,15].

In the present study, predictions of the core temperatures were made using a PHS program developed by Jacques Malchaire (last modified on June 2016, personal communication). The program analyses and interprets the heat stress using formulae based on ISO Standard 7933:2004 [Ergonomics of the thermal environment – Analytical determination and interpretation of heat stress using calculation of the predicted heat strain].

Predicted values from the PHS index were then compared with temperature readings obtained by a thermometer-based ingestible capsule (VitalSense® Core Temperature Capsule) that measures core temperature and transmits data in real time to a Sensor Electronic Module (SEM) wireless device. The VitalSense capsule is 8.6 mm in diameter, 23 mm in length and weights 1.6 grams with a temperature accuracy of ±0.1°C, over a range of 25°C to 50°C [17]. Once activated and ingested, individuals are required to be within a reception range of approximately 1 m from a portable monitor (EquiVital Life Monitor, Hidalgo Ltd. Cambridge, UK) that contains the SEM device. Core temperatures and other vital signs such as skin temperature, heart rate, and respiration rate are measured and reported at a rate of four times per minute to the monitor. Several research studies have supported the VitalSense capsules as a valid and reliable technique for the measurement
core body temperature in humans, especially in field-based settings [3,6,7,9,16]. Physiological data are downloaded from the SEM wireless device for analysis and comparison. The main objective of this study is to conduct an in-depth examination of the relationship between the VitalSense capsule and the PHS index, and to uncover the existence of any inconsistencies and differences between the two approaches.

2. METHODOLOGY

2.1. Participants and mining activities

All two experimental data sets—the VitalSense capsule and PHS index—presented in this study were derived from testing ten participants. Male participants recruited for this study were permanent and part-time workers at the mine who were asked to perform physically demanding tasks. The skill level and degree of difficulty of each activity were quite diverse and none of them had professional or elite physical training background. Table 1 shows the anthropometrical characteristics of all participants considered in the study.

**Table 1.**

*Anthropometrical characteristics of all participants in the study*

<table>
<thead>
<tr>
<th></th>
<th>Age (Years)</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
<th>BMI (kg/m²)</th>
<th>Living in AZ (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Males</strong> n=10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>21.16</td>
<td>65.8</td>
<td>180</td>
<td>23.89</td>
<td>7.93</td>
</tr>
<tr>
<td>STDEV</td>
<td>1.85</td>
<td>4.5</td>
<td>0.02</td>
<td>1.88</td>
<td>7.82</td>
</tr>
</tbody>
</table>

Mobile and real-time monitoring from the VitalSense system enabled the acquisition of physiological data for extended periods of time, while the ingestible pill was kept in the stomach. It allowed representative measurements of participants’ daily routines, whether they were performing underground work, such as drilling or mucking, or supporting other mining activities during the day, including surface-level tasks. Table 2 summarizes the
percentages related to activities at the underground and surface levels. Air temperature and relative humidity were input values for the PHS index. On average, underground air temperatures were slightly lower than at the surface level, while underground relative humidity values were slightly higher than those observed at the surface.

Table 2.
_Air temperature and Relative humidity averages at underground and surface levels_

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Total Mine</th>
<th>Full Year</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>U.G. Activities</td>
<td>Surface Activities</td>
</tr>
<tr>
<td>Air Temperature (°C)</td>
<td>25.28 ± 6.27</td>
<td>25.08 ± 6.68</td>
<td>25.82 ± 5.56</td>
<td>26.34 ± 6.37</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>27.77 ± 15.8</td>
<td>28.03 ± 17.2</td>
<td>27.10 ± 12.4</td>
<td>38.60 ± 7.5</td>
</tr>
<tr>
<td>% of Time</td>
<td>100%</td>
<td>81.4%</td>
<td>18.6%</td>
<td>-</td>
</tr>
</tbody>
</table>

The studies were held at Resolution Copper and San Xavier underground mines during consecutive seasonal periods from 2016 to 2018. Both mines are located in Arizona, a desert state in the United States largely characterized by its high temperatures and relative dryness. Experiments were conducted during daytime shifts (range times varied from 7 a.m. to 3:30 p.m.), where all participants were required to wear personal protective equipment consisting of helmet, goggles, gloves, special footwear and overalls. The rock temperature at Resolution Copper underground is about 80 °C, however, the air properties measurements were taken in cooled working areas.

A brief description of the physical demands of every working activity is provided below:
- Main workers: regularly required to stand and walk for extended periods of time through all operative underground levels of the mine. For maintenance supervisors, physical activity is moderate to heavy while operating the tools and materials.
- Drilling: driving and operating mobile drilling machines. Moderate physical strength is required to drill, wire and place explosives in a generally noisy and dusty work environment. Use of a jack hammer drill was performed also at the surface level.
- Mucking: the process of removing the broken material from the mining faces with a mucking machine. Operators are required to stand by the machine for long periods of time
- Shoveling: using a shovel as a tool for digging, taking up, removing and throwing loose material.
- Other activities: Physical activity required for cutting steel and maintenance work at the surface level.

2.2. Predicted Heat Strain experimental procedure

Required environmental parameters used as inputs for the Predicted Heat Strain model were measured after the initial participant health questionnaire was filled and every 60 minutes thereafter without interfering with the course of activities. The thermal insulation for the clothing ensemble considered was 0.5-0.8 clo, according to insulation values obtained with a thermal manikin for a similar clothing ensemble [10]. Air temperature and relative humidity were continually measured by a digital LCD Thermo-Hygrometer; the air speed was measured by an airflow anemometer (Airflow Developments Ltd, England), the globe temperature was calculated from the air temperature and solar radiation was obtained according to formulae derived in a thermal study for outdoors and indoors environments [5]. The globe temperature and solar radiation were also collected from the ‘Weather Underground’ website.

2.3. Core Temperature Capsule Procedure
VitalSense core temperature capsules (EQ-ACC-023) and EquiVital monitor (EQ-02-SEM-007) were used in this research. Participants were asked to use a chest belt (EQ-02-B2-1-TBD) to attach the monitor to the body and provide mobile monitoring capability. The VitalSense capsule was activated by placing it in front of the monitor activation port. Following activation, the capsule was swallowed, and transmission of temperature data began reading every 15 seconds. Capsules were administered to participants between 7 a.m. to 10 a.m. The experiment was completed when the data communication was no longer maintained, or when the capsule was passed.

2.4. Statistical Analysis

Core temperatures from the VitalSense capsule and the PHS index were averaged at 1-minute intervals during each working session for statistical comparison. Paired Samples t-test and the 95% confidence intervals (95% CI) were used to assess the relationship between the two temperature measurements. The level of significance was set at 5% (α=0.05) to evaluate the statistical differences, where a p value < 0.05 was considered statistically significant. Mean bias and limits of agreement (LoA) were investigated by plotting the temperatures differences between methods against their means according to the Bland-Altman method of measurement for multiple observations per subject [2]. It was not possible to properly correlate the results of the two methods due to missing Vital Sense data readings. The Pearson product-moment correlation was used to established data correlation. All data are reported as mean ± standard deviation.

3. RESULTS

For all 1-minute time periods, the average PHS Index core temperature ($T_{PHS}$) was $37.14^\circ C \pm 0.50^\circ C$ (95% confidence interval [CI] = 37.12 to 37.15°C) and for VitalSense
capsule core temperature ($T_{OBS}$) was $37.15^\circ C \pm 1.15^\circ C$ (95% confidence interval [CI] = 37.13 to 37.18$^\circ C$). The largest differences in core temperature between both measurements were found 5 minutes immediately after the capsule was ingested. For every pair of 8,143 core temperature data points, the $T_{PHS}$ value was subtracted from the $T_{OBS}$ value (Fig. 1). In this situation, the paired t-test yields no significant result between the $T_{PHS}$ and the reference $T_{OBS}$ on core temperature across both experiments datasets (A mean bias of 0.014$^\circ C$, 95% CI: -0.010 to 0.038$^\circ C$; P=0.250; t stat=1.15; t critical 2-tail=1.96), suggesting that both methods worked equally through all participant readings. However, drilling at surface was the only non-significant activity (See Table 3), while all the other activities displayed statistically significant differences (all p’s < 0.001). Also, the Pearson’s correlation coefficient shows a weak positive correlation (Pearson r=0.32, P<0.01), according to Evans [8] between all measurements combined for $T_{PHS}$ and $T_{OBS}$ datasets. Inter-class correlation coefficients also indicate poor reliability, the ICC for all pair comparisons was 0.377 (95% confidence interval [CI] = 0.349 to 0.404). Limits of agreement (LoA) were calculated as described by Bland and Altman for measurements of two methods with multiple and unequal observations by participants [2], determining that the mean and standard deviation of the difference of $T_{OBS}$ and $T_{PHS}$ are variable throughout the range of measurement (Fig. 2), with the 95% LoA between $T_{OBS}$ and $T_{PHS}$ as Upper limit: $Y=-68.54 + 1.81X$, and Lower limit: $Y=-67.44 + 1.84X$, for $Y: T_{OBS} - T_{PHS}$ , $X: (T_{OBS} + T_{PHS})/2$. 
Table 3.
*Ratings by type of measurements across activities*

<table>
<thead>
<tr>
<th>Activities</th>
<th>Core Temperature Means (°C) at 95% Confidence Limit</th>
<th>Pearson Correlation</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PHS Index</td>
<td>VitalSense pill</td>
<td></td>
</tr>
<tr>
<td>1. Main workers</td>
<td>36.35 ± 0.05</td>
<td>37.19 ± 1.08</td>
<td>0.18</td>
</tr>
<tr>
<td>2. Drilling UG</td>
<td>37.78 ± 0.58</td>
<td>37.06 ± 1.20</td>
<td>0.47</td>
</tr>
<tr>
<td>3. Drilling on Surface</td>
<td>37.10 ± 0.80</td>
<td>37.11 ± 1.15</td>
<td>0.49</td>
</tr>
<tr>
<td>4. Mucking</td>
<td>37.58 ± 0.17</td>
<td>37.22 ± 0.58</td>
<td>0.08</td>
</tr>
<tr>
<td>5. Maintenance on Surface</td>
<td>37.06 ± 0.16</td>
<td>37.23 ± 0.81</td>
<td>0.49</td>
</tr>
<tr>
<td>6. Shoveling</td>
<td>37.12 ± 0.09</td>
<td>39.91 ± 0.43</td>
<td>0.63</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>37.14 ± 0.50</td>
<td>37.15 ± 1.15</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Examining the results presented in Table 3, several observations can be made. For instance, for the fifth activity ‘Maintenance on Surface’ that was carried out in July 2017 (summer), the PHS index predicts the core temperature as one of its lowest (37.06°C), while the VitalSense pill gives a higher value (37.23°C). On the other hand, for the second activity ‘Drilling UG’ that was performed in winter, the PHS index predicted the highest core temperature. In addition, among the six field activities evaluated, the PHS index is in close agreement with the VitalSense pill only for ‘Drilling on Surface’, even though the p-value (0.594) suggests that the correlation is not statistically significant.
For mining activities broken down into underground and surface works, results confirm no significant difference between the PHS index and VitalSense methods related to core temperatures in underground environments (A mean bias of -0.016°C, \( P=0.249 \)), while the difference in core temperature means on the surface was significant (A mean bias of 0.15°C, \( P<0.001 \)).

The acquisition of core temperature readings from the capsule monitor was successful in 95.5% of experiments (4.5% data loss). Sources of interference, such as the proximity to running machinery or incorrect wearing of sensor belt account for the majority of lost data.

4. DISCUSSION

The primary purpose of this study was to validate the use of the PHS heat stress index for estimating the core temperature of acclimated mine workers performing typical duties. The PHS index core temperature values were validated with an established and highly accurate
technology, the VitalSense telemetric ingestible capsule. Although the paired t-test finds no statistically significant difference between the two methods (mean bias of 0.014°C, 95% CI: -0.010 to 0.038°C), the Pearson correlation coefficients and the Bland & Altman method provide a relatively weak correlation between both measurements. In this study, the subject’s average work load ranged from moderate to intensive. The subjects were instructed not to deviate from their regular eating and resting habits, which resulted in a high degree of variability in the physiological data in comparison with other well-controlled laboratory settings. The PHS index overpredicted core temperatures for low values as measured by VitalSense (<37.12°C), and conversely, underpredicted core temperature values for high values (>37.12°C). In general, the PHS index tends to underestimate critical values of thermal strain, which is in line with other studies [11] that reported underestimated rectal temperatures in the range of 37-38 °C. Examining all the data in Figure 3, it appears that the PHS index values approach a horizontal asymptote in the last hours of the experiments and tend to remain flat thereafter. This suggests that the PHS method should be analyzed in multiple phases i.e. when the task and environmental conditions change. This, however, differs from the original purpose of the PHS index created to predict an entire 8-hours shift.

As expected, lower levels of core temperature were predicted for mine workers (mean T_{PHS} = 36.35°C), and correspondingly, the heart rate levels experienced by the same workers (mean HR = 101 bpm) were also lower than for other activities. Interestingly, the values for light activities in Figure 3 showed higher discrepancy between predicted and observed core temperatures (T_{PHS} over-estimating core temperature in 0.82°C), although anthropometric characteristics (age, weight, height, health test) were not significantly
different from the rest of participants. One possible explanation may be the range of temperatures experienced by mine supervisors during long periods of walking through different levels of the mine, was only captured in real-time by the VitalSense capsule, in contrast to the PHS index which requires several input parameters reflecting the changing conditions in terms of work exposure and rest duration (VitalSense collects data more frequently compared to the PHS parameters that were updated only every 60 minutes). Similar time-varying effects on work exposure have been noted by others [12].

![Bland-Altman plots](image)

**Fig. 2** Bland-Altman plots of observed core temperature (VitalSense capsule) and predicted core temperature (PHS index), with means (solid line) and limits of agreement (dashed lines)

The observed discrepancy between the two methods when core temperatures are lower than 37.12°C is explained in part by the existence of dissimilar temperature readings at the start of experiments in both datasets. This is especially the case when the VitalSense capsule showed a steep increase in core temperatures immediately after the capsule was ingested. The temperature values continue to increase for about five to ten minutes, adjusting to changes between ambient temperature at the time of activation and when the capsule
entered the stomach. Although very low core temperature values were flagged as data loss
(hypothermia <35°C), the dynamic behavior of the VitalSense readings $T_{OBS}$ was lower
than the $T_{PHS}$ in the initial stage of the data acquisition. More importantly, less time was
observed (<1 min) in the case of the highest intensive activity (drilling underground) to
start reading the first acceptable core temperature values, suggesting a correlation effect
between delay and specific work activities.

Data collected during underground and surface activities provided the opportunity to study
in more details the effect of outdoor and indoor environments on participants’ core
temperatures. In general, cooler environmental conditions were observed underground,
especially during the summer, because the mine ventilation systems provided cooler air in
the working areas. Results from core temperature measurements indicate that the PHS
index and VitalSense pill methods showed better correlation for participants working
underground, i.e. smaller differences between predicted and observed core temperatures,
than subjects working on the surface level, albeit for small biases (-0.016°C and 0.15°C
mean bias in core temperatures, for underground and surface activities). These results
suggest that the PHS index ability to predict core temperatures increases in environments
where the heat load is less such as those found underground. It would also suggest that in
this study the statistical correlation was improved due to controlled changes in thermal
conditions underground, rather than other factors such as age, gender, body mass index or
acclimatization of participants who belonged to a relatively homogeneous population. In
other words, it appears that in this study, the PHS index showed very little sensitivity to
different anthropometric characteristics.
Fig. 3 Core temperatures observed (VitalSense capsule) and predicted (PHS index) for the six mining activities: (a) Main workers, (b) Drilling UG, (c) Drilling Surface, (d) Mucking, (e) Maintenance on surface, (f) Shoveling

5. CONCLUSIONS

This study assessed core temperatures provided by the predicted heat strain (PHS) index and a core temperature pill (VitalSense) for ten acclimatized participants at two underground mines. Comparisons were made between real time experimental data and the PHS model. It was found that the PHS model showed no statistically significant difference with the VitalSense (mean bias +0.014°C, 95% CI: -0.010 to 0.038°C) core temperature readings. However, the PHS index tends to underestimate higher core temperature values.

Conflict of Interest The authors declare that there is no conflict of interest.

REFERENCES

APPENDIX C – MANUSCRIPT 3
APPENDIX C - DEVELOPMENT OF A MODIFIED PREDICTED HEAT STRAIN MODEL FOR HOT WORK ENVIRONMENTS

Paloma Lazaro ¹, Moe Momayez ¹

¹ Department of Mining, Geological & Geophysical Engineering, University of Arizona
1235 James E. Rogers Way, Tucson, AZ 85719 United States
E-mail: plazaro@email.arizona.edu; Tel. (720) 256-6850

Keywords: Predicted heat strain; Hot underground mines; Heat strain; Heat stress

Published 04 July 2020 in the International Journal of Mining Science and Technology
ABSTRACT

Excessive exposure to heat can lead to injuries, illness, and death among mineworkers. The actual cost of heat-related injuries and illnesses is unknown because of underreporting and lack of symptom recognition. Multi-factorial, evidence-based, and field-ready guidelines for identifying—and predicting—physiological markers of heat strain are currently unavailable. The predicted heat strain (PHS) model, is the latest attempt by mining companies to aid in the evaluation and management of occupational heat exposures. The adopted algorithm relies on worksite environmental measurements and an estimate of individual metabolic rate for mine workers to provide an estimate of the workers’ core temperature during a work shift. There are several known limitations of the PHS model, including the assumption that the subject worker is hydrated and fit. A modified PHS model was presented based on eight physical parameters that are measured at different intervals during a work shift; these parameters are air temperature, relative humidity, air velocity, radiation, metabolic rate, acclimatization, clothing insulation and posture. To validate the results, the predictions from the modified PHS model were compared with direct physiological measurements obtained from ingestible pills and heat stress monitors under different environmental and working conditions.

1. INTRODUCTION

The predicted heat strain (PHS) index (ISO Standard 7933, 2004) is one of the rational indices developed over the past fifteen years through which a vast range of rigorous scientific evidence has been applied to predict the thermal stress experienced by humans.
Nowadays, the PHS index has gained a widespread use in industries such as construction, sports and the army, and the mining industry is adopting the standard to establish their own heat stress management practices to provide safe working conditions to person and equipment, especially at great underground depths [1-4]. One of the most beneficial features of the PHS index, its ability to predict limiting thermal exposure in heavy industries settings, makes this index appealing for heat stress monitoring. However, in a larger context of predicting successive stages of an intermittent work exposure, the applicability of the PHS index has not been successfully established [5]. Except for research work reported in the literature examining critical factors that impacted the performance of the PHS index such as the small size of the European population used in the original validation and its limited ability to respond under extreme environmental conditions, the authors are not aware of any study that investigated the intrinsic relationship based on which the PHS index is formulated [6-8]. The present study explores in detail the PHS theoretical model proposed by Malchaire and others, reviews the basis of its formulation in the form of the thermal balance equation, modifies one of the main equation for calculating the core temperature, and verifies the modified PHS model against a direct physiological measurement.

The PHS model replaced the 1989 version of the required sweat rate index (ISO 7933, 1989) by improving important aspects of the algorithms of clothing ensembles, maximum exposure times, formulas and practicability of the model. It involved the participation of state-of-the-art laboratories and heat stress researchers of the principal European scientific centers in the field of physiology [9]. The PHS model turned out to be the most scientifically advanced of the indices in the matter. It allows a very rigorous approach to
the calculation and prevention of thermal risks found in the environment, by predicting physiological characteristics such as the core body temperature, sweat rate and rectal temperature in a fifteen-seconds-resolution collected data. The model was validated by a considerable number of field (237) and laboratory (672) experiments made by the eight main European research [9,10]. In the present study, a modification of the PHS model was carried out on the expression that relates the core temperature as a function of the skin temperature: a multiple linear regression was conducted on site to derive an algorithm that estimates core body temperature ($T_{cr}$) from skin temperature ($T_{sk}$) and heat storage. The model was updated directly from an excel PHS program written and provided by Malchaire which analyses and interprets the heat stress using formulae based on ISO Standard 7933, 2004.

Core temperature values from the modified PHS model are compared against core temperature readings from a wireless telemetric monitoring system (VitalSense® Core Temperature Capsule). Both measurements were taken simultaneously under the same working circumstances by participants. The VitalSense capsule is a 23 mm length, 8.6 mm in diameter, and 1.6 g in weight pill with a ±0.1°C temperature accuracy if administered in an environment whose ambient temperature range from 25°C to 50°C [11]. The VitalSense capsule reads core temperature (in addition to measuring the heart rate) and transmits that data in real time to a wireless sensor device (Sensor Electronic Module, SEM). After ingestion, participants were required to carry on a monitor with them (EquiVital Life Monitor, Hidalgo Ltd. Cambridge, UK) that contains the SEM device, and be within a radius of 1 m from the portable monitor always while the experiment is in progress. Several research publications have validated the use of the VitalSense capsule as a reliable and
practical method to measure core human body temperatures in the field and laboratory settings [12-15]. Experiment data is stored in the SEM device and is further downloaded for analysis. It is the purpose of this study to examine the relationship between the VitalSense capsule and the modified PHS index and validate the existence of any consistent differences between both measurements. In addition, the modified PHS index outcomes have been compared with results from the original PHS index fed with the same input data sets.

2. CORE TEMPERATURE ($T_{CR}$) AND SKIN TEMPERATURE ($T_{SK}$)

Formulae used for the PHS index are subject to further testing and refinement. Regarding the “distribution of the heat in the body”, the PHS index estimates the core temperature as a function of the skin temperature and heat stored, and assumes that inside the skin, temperature behaves linearly from $T_{sk}$ to $T_{cr}$. Since our study measures real data on core and skin temperature, a multiple linear regression analysis has been performed to derive an expression to predict $T_{cr}$ from two other independent variables: $T_{sk}$ and Heat stored. Our approach respects the linearly assumptions, and theoretically solves the equation:

$$T_{cr} - T_{cr0} = \varepsilon + \alpha' (T_{sk} - T_{sk0}) + \beta' \text{dStoreq/spHeat}$$

(1)

where $T_{cr}$ is the core temperature measured by the ingestible capsule (VitalSense® Core Temperature Capsule); $T_{sk}$ the skin temperature measured by a self-adhesive dermal temperature patch (VitalSense® Dermal Patch); $T_{cr0}$ the body core temperature at time zero; $T_{sk0}$ the skin temperature at time zero; dStoreq the heat storage associated with the $T_{cr}$; spHeat the specific heat (kg.); $\varepsilon$ the constant; and $\alpha$ and $\beta$ the coefficients. Heat stored
was calculated from the heat balance equation. A total of 563 data points for $T_{cr}$, $T_{sk}$, and $d_{Storeq}$ were collected to allow a statistically sound conclusion of the multiple linear regression analysis to be reached.

The values of the regression coefficients $\alpha$, $\beta$ and the constant $\varepsilon$ as determined by the multiple linear regression for the experimental data are $\alpha=0.06902$, $\beta=-82.61$, and $\varepsilon=35.64$. The standard error of the estimate was calculated to be 0.2095, and the standard error of the partial regression coefficients $\alpha$ and $\beta$ is 0.3782 and 0.2167, respectively. Table 1 summarizes the results of the multiple linear regression, including the multiple correlation coefficient ($R$), the goodness of fit ($R^2$), regression coefficients, and the associated standard errors. An analysis of variance was performed where both regression coefficients were found to be highly significant. The effect of $\alpha$ is significant at the $p=0$ level and the effect of $\beta$ is $p=0$. This indicates that skin temperature as well as heat stored are both significant predictors of body core temperatures. Table 2 shows the results of the analysis of variance in terms of the degrees of freedom (DF), sum of squares (SS), mean sum of squares (MSS), the significant level of each parameter and for the entire equation ($p$), and the $F$-ratio.

**Table 1** Multiple linear regression results.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>adj. $R^2$</td>
<td>0.86</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.861</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>35.64 (±0.3915)</td>
</tr>
<tr>
<td>$T_{sk}$</td>
<td>0.06902 (±0.01089)</td>
</tr>
<tr>
<td>$d_{Stored/spHeat}$</td>
<td>-82.61 (±2.3197)</td>
</tr>
</tbody>
</table>
Table 2: Analysis of variance of multiple linear regression equation of core temperature $T_{cr}$ with two independent variables, with no restrictions in the design. $\Delta T_{cr}=35.64+0.06902*\Delta T_{sk}-82.61*d\text{Storeq/spHeat}$.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>DF</th>
<th>SS</th>
<th>MSS</th>
<th>F-ratio</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined effect of $\alpha$ and $\beta$</td>
<td>2</td>
<td>151.9980</td>
<td>75.9990</td>
<td>1730.8871</td>
<td>1.8E-240</td>
</tr>
<tr>
<td>Test of $\alpha$</td>
<td>1</td>
<td>96.3160</td>
<td>96.3160</td>
<td>673.1420</td>
<td>4.11E-98</td>
</tr>
<tr>
<td>Test of $\beta$</td>
<td>1</td>
<td>150.2326</td>
<td>150.2326</td>
<td>3198.0691</td>
<td>0</td>
</tr>
<tr>
<td>Residual</td>
<td>560</td>
<td>24.5882</td>
<td>0.0439</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Total</td>
<td>562</td>
<td>176.5862</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The new expression of core temperature $T_{cr}=f(T_{sk}, d\text{Storeq/spHeat})$ is the only modification introduced to the original PHS index while all other criteria and formulae used by Malchaire et al. for predicting the thermal strain remain the same. In other words, the proposed modified PHS index has the same as Malchaire’s algorithm, which can be adapted accordingly to reflect any required modification. In this case, the modified PHS algorithm does not add any computational burden compared to the original, slightly reduces its complexity and provides better data reproducibility. It is important to note that although our new expression is mathematically sound, the predicted values may be influenced by restricted convective heat transfer and excessive water infiltration, conditions that are similar to those found in the two underground mines where our studies were conducted [16].

3. VALIDATION OF THE MODIFIED PHS INDEX

3.1. Participants

Ten healthy young (age: (21.16±1.85) years) male volunteer participants (weight: (65.8±4.5) kg, height: (1.74±0.06) m) were recruited for this study. All participants were physically active but without high level competences in sports. They were informed about
the experimental procedures, risks and safety concerns in the use of portable equipment and were required to sign a letter of concern before their participation in the study. All experiments were held at the San Xavier and Resolution underground mines, located in the state of Arizona during different sessional periods. Experiments were performed during day shifts from 7 am to 3:30 pm and participants were required to wear personal protective equipment such as gloves, hard hats, eye protection, steel toe boots, earplugs, and full body suits. Eight different physical parameters were measured on every participant. Table 3 shows the mean and standard deviation of the studied parameters recorded on all participants of the study.

Operational mining activities evaluated in this study included drilling, mucking, shoveling, mine maintenance, foreman work performed underground, as well as other work tasks observed at the surface level.

**Table 3** Mean and standard deviation of main parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature, $T_a$ (°C)</td>
<td>25.28</td>
<td>6.27</td>
</tr>
<tr>
<td>Relative humidity, $H$ (%)</td>
<td>27.77</td>
<td>15.76</td>
</tr>
<tr>
<td>Radiation, $T_r-T_a$ (°C)</td>
<td>27.75</td>
<td>20.02</td>
</tr>
<tr>
<td>Mean radiant temperature, $T_r$ (°C)</td>
<td>53.03</td>
<td>15.98</td>
</tr>
<tr>
<td>Air velocity, $V_a$ (ms$^{-1}$)</td>
<td>1.58</td>
<td>0.85</td>
</tr>
<tr>
<td>Metabolic rate, $M$ (W)</td>
<td>156.36</td>
<td>35.13</td>
</tr>
<tr>
<td>Clothing insulation, $I_d$ (clo)</td>
<td>0.77</td>
<td>0.09</td>
</tr>
<tr>
<td>Partial vapor pressure, $P_a$ (KPa)</td>
<td>0.92</td>
<td>0.50</td>
</tr>
<tr>
<td>Globe temperature, $T_g$ (°C)</td>
<td>33.46</td>
<td>3.62</td>
</tr>
</tbody>
</table>

3.2. **PHS index and modified PHS experimental procedure**

Inputs needed to run the PHS index, and the modified PHS models are essentially the same: anthropometric characteristics of participants (weight, height, and acclimatization) and specific parameters of the work (See Table 3). Air temperature, humidity, air velocity,
globe temperature, and metabolic rate were taken every 60 minutes approximately, without interfering the normal course of activities in the two underground mines. The thermal insulation considered ranged from 0.5 to 0.8 clo, based on intrinsic insulation estimations for different clothing ensembles received with a manikin under similar clothing conditions than the ones used for our participants [17]. Air velocity ($V_a$) was measured by the airflow anemometer (Airflow Developments Ltd, England). Air temperature ($T_a$) and relative humidity ($H$) were measured by a digital LCD Thermo-Hygrometer, solar radiation was taken by a weather station online network, and globe temperature ($T_g$) was deduced from the solar radiation and air temperature [18].

3.3. VitalSense capsule procedure for core temperature

One VitalSense core temperature capsule (EQ-ACC-023) was administered to every participant prior to the start of daily activities. Temperature data was transmitted and recorded every 15 seconds. The EquiVital Life monitor (EQ-02-SEM-007) was attached to the chest belt (EQ-02-B2-1-TBD) to provide hands-free operation. Data collection was stopped at the end of the shift–around 3:30 pm. Experiments were performed on separate days for each subject.

3.4. Statistical analysis

The PHS index and the modified PHS model were programmed to predict core temperature at a rate of one point per minute, while the VitalSense capsule transmitted core temperature reading four times per minute. For statistical comparison, the predicted core temperature values from the PHS index, the modified PHS, and the VitalSense capsule
were averaged separately at 1-minute intervals for all working experiments. The paired samples (t-test) was used to compare the means between the datasets and a 95% confidence interval (CI) were employed to assess the statistical difference between the three sets of temperature measurements. The significant level was set to 5% (α=0.05), where a $p$ value <0.05 was considered statistically significant. The Bland-Altman method of measures with multiple observations per subject provided the upper and lower limits of agreement (LoA) and the mean bias between measurements by plotting the temperature difference against the instantaneous mean temperatures (at every 1-minute interval) [19]. Missing values (about 5.1% of the total data) from the VitalSense readings were discarded from the study. The Pearson and Kappa correlation coefficients were used to assess any positive or negative linear correlation between these two variables. All data are shown as mean±standard deviation.

4. RESULTS

4.1. PHS index and VitalSense capsule

Core temperature data points (7527) were obtained simultaneously from intermittent work exposure for all ten participants. The average core temperature was (37.149±0.36)°C (95% confidence interval CI=37.14°C to 37.16°C) and for the VitalSense core temperature capsule was (37.123±1.11)°C (95% confidence interval CI=37.10°C to 37.15°C). The t-test results were found to be statistically significant ($p<0.05$) for the sample pair PHS index-VitalSense. However, a noticeably weaker correlation exists between the PHS index and VitalSense capsule (Pearson and Kappa correlation of about 0.232 and 0.352, respectively) as compared with the ones obtained by the modified PHS and VitalSense
(Pearson and Kappa correlation of about 0.449 and 0.429, respectively). Table 4 cross-tabulates the Pearson and Kappa correlation coefficients related to the three heat strain assessment metrics for core body temperatures during summer (hot climate) and the full year.

**Table 4** Core temperature means (°C) for the entire year and summer session; and Pearson and Kappa correlation coefficients between metrics based on modified PHS, VitalSense pill and PHS index models.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Core temperature means (°C) at 95% CI</th>
<th>Pearson Correlation</th>
<th>Kappa Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full Year</td>
<td>Summer</td>
<td>Modified</td>
</tr>
<tr>
<td>Modified PHS</td>
<td>37.146 ± 0.45</td>
<td>37.131 ± 0.40</td>
<td>-</td>
</tr>
<tr>
<td>VitalSense Pill</td>
<td>37.123 ± 1.11</td>
<td>37.391 ± 1.13</td>
<td>0.449</td>
</tr>
<tr>
<td>PHS index</td>
<td>37.149 ± 0.36</td>
<td>37.085 ± 0.50</td>
<td>0.273</td>
</tr>
</tbody>
</table>

### 4.2. Modified PHS and VitalSense capsule

A similar experimental procedure was used to run the modified PHS index (7527 core temperature data points for all participants). The average core temperature for the modified PHS model was (37.146±0.45) °C (95% confidence interval CI=37.14°C to 37.16°C) in line with the PHS index results and greater in about 0.023°C compared with the VitalSense capsule. Statistically significant relationships were found for all participants for both underground mines and for all activities together (p<0.05). The largest differences between data points were observed at the beginning of a work session. An example of an individual core temperature measurement is shown in Fig. 1, which corresponds to a 3-hour drilling activity at the San Xavier underground mine. For the entire set of experiments, Fig. 2 shows all core temperatures measured, from the modified PHS index ($T_{c_{-Modified PHS}}$) against the VitalSense capsule values ($T_{c_{-VitalSense}}$). In this situation, the paired t-test yields statistically
significant result between the modified PHS index and the reference VitalSense readings for core temperature across both experiments (mean bias of 0.023°C; 95% CI: -0.001°C to 0.044°C; \( p < 0.05 \); \( t \) stat=1.97; \( t \) critical 2-tail=1.96), suggesting that both methods worked differently through all participant’s readings.

Fig. 1. An example of an individual core temperature measurement.
Fig. 2. VitalSense core temperature (observed) and PHS index temperature (predicted) over time for the entire time of experiments.

Pearson correlation coefficient shows a moderate positive correlation (Pearson r=0.45, p<0.01), according to Evans between all measurements from both datasets [20]. Limits of agreement (LoA) as described by Bland and Altman determined that the mean and standard deviation of the difference between $T_c$ (VitalSense pill) and $T_c$ (modified PHS) are variable across the range of measurements (Fig. 3), with a 95% LoA between both measurements as upper limit of 1.11 and lower limit of -1.07 [19]. The EquiVital Life Monitor readings were successful in 94.9% of the cases (with a data loss of 5.1% in cases where participants were more than 1-meter away from the monitor, incorrect use of the sensor belt, or if electromagnetic interference or machinery influenced proper readings).
5. DISCUSSION

This study sought to develop a modified version of the PHS heat stress index (ISO Standard 7933, 2004) to give more accurate core body and skin temperature predictions. Modifications were made to the existing formulae regarding the distribution of the heat on the body by developing a new expression that relates the core temperature as a function of the skin temperature and the heat stored, assuming a linear relation between $T_{sk}$ and $T_{cr}$. A multiple linear regression analysis was carried out to predict the core temperature (dependent variable) of an individual performing an intermittent work as a function of the skin temperature and heat storage (independent variables) at time “$t$” (from 0 to 480 min). The multiple regression coefficient ($R^2$) was high (0.861), and at the same time the $F$-ratio was 1731, indicating that the overall regression was highly significant. The proposed
expression to calculate core temperature replaces the empirical approach by Malchaire et al. where it was assumed that the core-skin weighting was constantly increasing over time, which is not always the case. The modified PHS index core temperature values were validated using measurements made with an established and highly accurate technique, the VitalSense telemetric ingestible capsule.

As described above, the proposed modified PHS index employs a fundamentally different approach to predict core body temperatures. The paired t-test marginally finds a statistically significant difference between the modified PHS and the VitalSense method (mean bias of 0.023°C, 95% CI: -0.001°C to 0.044°C), although the modified PHS predictions are closer to the actual core temperatures compared with the PHS index/VitalSense results (mean bias of 0.026°C, 95% CI: -0.002°C to 0.050°C), confirming that our proposed method provides a better performance. More importantly, the modified PHS method improved the correlation coefficients from weak to moderate for both the Pearson and Kappa correlation metrics (See Table 4). These results suggest that the sole relationship between $T_{cr}$ and $T_{sk}$ could be a critical factor that explains the poor estimations of core temperature reported by other investigators when the PHS index is used [21-24]. However, a moderate correlation does not imply higher degrees of accuracy across the board. For example, as shown in Table 4, in the summer season the average core temperatures were obviously higher than for the full year when measured by the VitalSense pill (+0.268°C), but slightly lower than those obtained by the modified PHS (-0.15°C) and PHS index (-0.64°C).

Another advantage of the modified PHS method is that the proposed equation is based on the regression analysis relating the $T_{cr}$ and $T_{sk}$ and can be easily updated for any site-
specific environment without the use of sophisticated coding techniques compared to the PHS index algorithms. The modified PHS model also provides more versatility in terms of data processing and therefore can be used in a wider range of applications. However, it is important to note that the equation developed in this study is based on data obtained from a population of 10 young healthy men and should not be applied to a sample of subjects with different anthropometric characteristics. As a result, a generalization of the regression line is intrinsically limited by the input values to derive the equation. A further point to consider is that assessing the goodness-of-fit of the regression model will require the use of a separate data set to generate unbiased estimates of generalization errors.

Since the present study was not conducted in a well-controlled laboratory environment, and because participants were instructed not to deviate from their regular work routine and behavior, it is possible that a higher degree of variability in the physiological data is present. Predicted core temperature values from the modified PHS index closely follow the readings from the telemetry system for temperatures less than 37.2°C (See Bland-Altman plots, Fig. 3). However, for temperatures greater than 37.2°C, the modified PHS tends to underpredict core temperatures suggesting that the dispersion in the standard deviation of the mean influences the prediction performance of the method.

As noted previously, the present study considered several underground activities. It was observed that the activity that showed the lowest predicted core temperature values was supervision (modified PHS value=36.35°C). As expected, the heart rate of mine supervisors was around 101 bpm, lower than other mining activities. In contrast, drilling and mucking activities produced the highest values for the core temperature, often surpassing 38°C. Because of the limited scope of this work, the data from all activities were
aggregated into one set in order to identify patterns and trends. A more comprehensive investigation involving the collection and analysis of datasets from separate activities will help to develop a model for a specific activity thus improving the prediction power of the modified PHS index.

During the initial stage of each experiment (first 5 minutes), it was observed that the VitalSense capsule shows a steep increase in core temperature readings. This happens after activation of the capsule, when the subject ingests the pill followed by the passing of the pill into the stomach. It also explains the observed discrepancy between the PHS and the modified PHS methods. However, these initial low values of the core temperature did not indicate any subnormal body temperatures. For the purpose of the data analysis, very low core temperature values were categorized as data loss and were thus excluded from the analysis. For intense work activities such as drilling underground, it was observed that less time (<1 min) is required to obtain representative core temperature values, suggesting the impact that a specific mining activity has on the quality of the data.

6. CONCLUSIONS

A modified PHS model was developed to assess body core temperatures in hot work environments. The modification is based on a new expression that relates the core temperature as a function of skin temperature and stored heat. The modified PHS model has been validated against telemetry pill system (VitalSense capsule) for core body temperature measurement and compared with the original PHS index. The study involved ten participants who were representative of a larger mine workforce in two underground mines in Arizona. Multiple observations were made per individual and all core temperature
measurements were taken on different days and during normal shift periods. It was found that the modified PHS provides more accurate results than the original PHS index in terms of predicting core body temperature and improves statistical correlation and agreement.
REFERENCES


APPENDIX D – THE EFFECTS AND PERCEPTUAL RESPONSES OF COOLING TECHNOLOGIES MONITORED DURING MINING ACTIVITY

Veronica Cordova¹, Paloma Lazaro¹, Moe Momayez¹

¹ Department of Mining, Geological & Geophysical Engineering, University of Arizona
1235 James E. Rogers Way, Tucson, AZ 85719 United States

Keywords: Cooling vest; Mining Industry; Perceptual heat stress; Field Study; Hardhats' color; Heat absorption
ABSTRACT

Different mining activities remain under the shadow of heat stress risk due to environmental conditions during the mine operations. In this project, the performance of three commercial cooling vests and a set of evaporative cooling cap and sleeves are evaluated by monitoring miners' activity and collecting perceptual responses. The perceptual comfort levels attained by miners using different cooling vests are estimated by individual and per group activity. A total of 92 wear trials involving 23 miner operators were conducted. Each wear trials consist of wear a cooling device at the hottest time of their activity without disturbing their ordinary labor. The miners rated their perceived exertion (RPE), Thermal sensation (TS), and five other subjective properties. The influence of hardhats' color on heat absorption is also studied by measuring the highest temperature reached during the shift. The study was performed on real mining activity during the hot summer in Arizona mine.

INTRODUCTION

Heat Stress (HS) has been present in the mining industry since the beginning of the days, and the criteria for recommended standards to work in Hot environments were introduce in 1972 by the National Institute of Occupational Safety and Health [1]. However, until these days, the rate of heat-related illness (HRI) in the US mining industry shows an increasing tendency, and HS is considered one of the deadliest weather-related health outcomes in the US [2,3].

In the surface mining industry, most of the HRI occurred during the summer day shift hours, given the increased solar radiate heat load and higher air temperatures [4]. Miners
in Arizona are particularly susceptible to heat-related deaths, and Arizona represents one of the primary three states with the highest numbers of heat-related deaths. In addition to work-related illnesses, workplace heat exposure can also increase the risk of occupational injuries and accidents [4,5].

Heat stress is a combination of environmental, work, and clothing factors that tends to increase body temperature, heart rate, and sweating [6]. Risk factors that contribute to encounter HS at the mine are listed: work demands (heavy physical labor, isolated work, working with a heat source); climatic conditions (direct sun exposure, high temperature, and humidity, non-breeze or wind); non-breathable clothing; individual conditions (acclimatization, hydration habits).

The dynamic activity in the field characterizes the mining worker. A way to reduce the heat accumulated in the body is to improve the microclimate of the person. Based on the HS risk factors, we identify five groups that are exposed to heat stress at the surface mine during the summertime. These groups are composed by mining operations (activity under the direct sun); hydrometallurgy (hot and humid environment and non-breathable clothing); mill (hot environment, dust, and clothing); geology (activity under direct sun and isolated work); and other activities like panel solar farming and construction.

In this field study, we focus on the first group: mining operation. This group comprehends the mining activities that are exposed to direct sun. The activities are held by pit geologists, pit maintenance mechanics (planned maintenance and on-site overhaul), blasters (arrange and samplers), surveyors, and electricians.
The conventional method for attenuation at the surface mine is training, maintained hydrated, and take rest schedules at the truck (A/C access). In this study, cooling vests are used to improve the microclimate of the mining operators.

Cooling vests have been proposed in a wide variety of industries to attenuate Heat stress. We can find aerospace, surgeries, sports, construction, crop production, motorcycle, and other industries. They were initially starting for the aerospace industry to improve the microclimate under the astronaut's suits. Most of these studies were carried out in laboratories, or they did not represent the mining activities. Few studies have assessed cooling interventions using mine rescue workers at the mine sites during the mine rescue training [7].

More than 30 types of cooling vests can be found in the market. The mechanism categorizes the cooling devices. Furthermore, the categories are evaporation, phase change material (PCM), air/water perfusion, fan cooling vest, and a hybrid cooling vest developed (a variation of PCM with fan vest) [8]. We used three of the most common commercially cooling vests (evaporative, PMC, fan vest) and a set of evaporative cooling cap and sleeves.

This study aims to conduct a field study in surface mines of Arizona to measure the perceptual responses of the intervention on professional mining workers. The cooling vest is worn in the middle of their activity or at the hottest point of the day. At the end of the shift, we collect the subjective ratings on the corresponding cooling vest: perceived cooling effect, perceived sweating rate, comfort sensation, perceived weight and perceived cooling time.
In the mining realm, a variety of hard hat colors can be found. The colors could follow a color code or not. Because of that, two miners from the same crew can have different hard hats color. In metal/nonmetal mine, MSHA does not regulate the hard hat coloring. On coal mine provides the following standard: "Distinctively colored hard hats or hard caps; identification for newly employed, inexperienced miners"[9].

The two primary classes of hard hats commonly used on mine sites are Class G-General ANSI Z89.1-1997 and Class E-Electrical [10]. These hard hats come in a variety of colors.

"The heat, which is absorbed by color, influences the microenvironment of man and many of his possessions. The three attributes of the color (hue, lightness, and saturation) influence the heat absorption of the object"[11]. For that, we measure and compare the highest temperature recorded in six hardhat colors (white, black, brown, blue, grey, and yellow). The white hardhat is used as a control.

Figure 1. Distribution of the mining operators crew by activity.
2. METHOD

2.1. Field Study

To evaluate the effects of the cooling methods, a field study at an Arizona surface mine was conducted during the summertime (August 2019). The field study involved one entire crew out of the four that rotates in a DuPont shift schedule.

The study consists of a four-day wear trial (one day per cooling method). The cooling methods: evaporation set (EV), evaporation vest (EV), fan vest (FV) and PCM vest (PCMV) were assigned randomly in 7 days in two consecutive day duty terms. The study finalized when the operator completed 4 valid trials.

Participants received a presentation with the objectives and purposes of the study and were aware of dropping the study or skipping the trial day. The volunteers and supervisors were instructed about the use and the care of each cooling vest. They also were notified about the application of the Telatemp non-reversible temperature recording labels (Telatemp) on the hardhats.

The first day the miners completed a survey with demographic information. The next days, the process consisted of pick up the surveys (2 performance surveys pre and post-trial and 1 activity log survey), the assign cooling vest and the telatemp label at the beginning of the daily safety meeting. The operator was instructed to divide their work in two sections, was the first section is used as a control was at the end. They complete the pre-trial performance survey and the second section, where they started wearing the cooling vest assigned. The trial ends when the miner decided to wear off the cooling method and complete the post-trial performance survey. At the end of the shift, the miners returned the cooling method, the surveys, and the set of telatemp used.
2.2. Participants

A total of 23 surface miner operators volunteered for the cooling method study. They worked on their regular activities in the mining operation crew that is distributed, as shown in Figure 1. The demographic characteristics of the participants are summarized in Table 1. The sample size formula is utilized to calculate the percentage of error in making inferences about the total population (4 crew = 92 miners) and ensure sufficient statistical power. One entire crew out of the four were studied, and that gave us an 18% margin of error to work.

Table 1. Demographic data of the exposed operation crew

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
<th>Mean (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (year)</td>
<td>24-59</td>
<td>35.39 (8.08)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>158-191</td>
<td>175 (10)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>57-110</td>
<td>80.17 (12.13)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>19-30</td>
<td>26.08 (30.15)</td>
</tr>
<tr>
<td>Gender (number of male and female)</td>
<td>20/3</td>
<td></td>
</tr>
</tbody>
</table>

2.3. Cooling devices and telatemp

Evaporation set (EV) composed by an evaporative cap and sleeves needs to be immersed in cold water and could last up to 20 min.

Evaporative cooling vest (EV) gets activated with the airflow, where the heat of the body and the environment produce the water to evaporate and keep the vest cold.

Fan vest (FV) circulate air to different speed from outside to inside. It utilizes a single lithium battery and can run for 8 hours.

Phase-changing cooling vest (PCMV) utilizes a frozen-hydrated salt to absorb body heat as a function of its specific heat capacity as a solid. As the heat transfers from the warmer
body to the ice packs, the phase change material will become liquid and warm to the
temperature of the environment around it.

Telatemp Non-Reversible Temperature Recording Labels (Telatemp) is an irreversible
temperature indicator label contains one or more sealed temperature-sensitive chemical
indicators that turn permanently and irreversibly from silver to black at its calibrated
temperature.

Response time is less than five seconds with an accuracy of ±2% or 1-°C of rated value,
whichever is greater.

2.4. Survey questionnaire

Two performance questionnaires were handled to the miners. The first questionnaire is
for the first section of the job(pre-trial), where they evaluated the rating of physical
exertion (RPE) on a scale from 0 to 10 where 0 is resting, and 10 is maximal activity.
They also assess the thermal sensation (TS) on a scale from 1 to 7, where one is very cold
and seven is very hot.

For the post-trial questionnaire, the miners evaluate the RPE, TS, and five subjective
attributes on a scale from 1-7. Perceived cooling effect (minimum-maximum), perceived
sweating rate (minimum-maximum), comfort sensation (minimum-maximum), perceived
weight (very light -very heavy), and perceived cooling time (1-7).

3. DATA PROCESSING

3.1. Perceptual heat strain index (PeSI)

PeSI measures the perceptual heat stress based on the parameters of thermal sensation
(TS) and perceived exertion intensity(RPE). In this study, we used the modified version
of the formula (Eq. (1)) proposed by Yang and Chan in 2015. The variation of the equation consists of redefining the range of scale of TS [12, 13].

\[ PeSI = 5 \times \frac{RPE}{10} + 5 \times \frac{(TS-1)}{6} \] (1)

Where RPE is the rating of physical exertion (from 0 to 10), and TS is a thermal sensation (from 1-7).

3.2. Physical Strain Alleviation (PSA)

PSA measures the percentage of the alleviation generated by using a particulate cooling method based on the RPE parameter. This formula was defined by Yang and Chan in 2015 [12] (Eq.(2)).

\[ PSA(\%) = \frac{RPE_{with} - RPE_{without}}{RPE_{without}} \] (2)

Where \( RPE_{without} \) is the RPE after completing the first half of the job without wearing any cooling method. The \( RPE_{with} \) is the RPE after completing the second half of the job wearing the cooling method.

3.3. Perceived Cooling Time (PCT)

PCT measures the cooling time perceived in hours by the participants. The equation proposed by Yang and Chan in 2015 [12] Eq.(3)

\[ PCT_{(hour)} = 0.5a_{(0.5)} + 1.0a_{(1.0)} + 1.5a_{(1.5)} + 2.0a_{(2.0)} + 2.5a_{(2.5)} \] (3)

We modified the equation according to the range of times established in our performance survey (Eq.(4)).
Where $PCT_i$ is the cooling time wearing a type of cooling method ($i =$ “1” represent ES, $i =$ “2” represent EV, $i =$ “3” represent FV, $i =$ “4” represent PCMV)

4. RESULTS

The mean value and the standard deviation of the temperature measured by the in-site weather station was 37(0.9) °C recording during the field study at the mine.

4.1. Rating on subjective attributes

In Table 2, Anova revealed a significance difference between the rating of 5 subjective attributes across the different cooling methods. EV shows a higher favorable rating in perceived cooling effect, comfort sensation, perceived cooling time, and observed weight(light) in comparison with the other three cooling methods. However, it also faces a higher number of perceived sweating rates (higher the number, higher the sweating rate), which goes along with the garment properties of the cooling vest (50% polyester and 50% polyurethane leather). The PCVM shows positive values above three on a linker seven scale on perceived cooling effect, comfort sensation, and perceived cooling time. However, it also presents a higher negative value on the perceived weight(heavy), where is ranked the heaviest method). The perceived sweating rate is also high, which means
that the miner sweat more than usual. FV results are minimum at perceived cooling effect, comfort sensation, and perceived cooling time. This cooling method was not able to demonstrate a cooling effect on the participants since the ambient temperature of the air was hot, and the air circulating inside the body was as well. The miners reported redness on the skin and high discomfort by wearing this device. ES has low values on perceived cooling effect, comfort sensation, and perceived cooling time. However, it has positive benefits on the perceived sweating rate and weight, which makes this cooling method the complement cooling method (figure 2).

Table 2.

<table>
<thead>
<tr>
<th>Subjective Attributes</th>
<th>ES</th>
<th>EV</th>
<th>FV</th>
<th>PCMV</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perceived cooling effect</td>
<td>2.52 (0.62)</td>
<td>4.65 (0.69)</td>
<td>1</td>
<td>4.48 (0.81)</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Perceived sweating rate</td>
<td>1.26 (0.20)</td>
<td>4.48 (0.72)</td>
<td>2.43 (0.89)</td>
<td>3.09 (0.90)</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Comfort sensation</td>
<td>2.83 (0.42)</td>
<td>4.30 (1.49)</td>
<td>1</td>
<td>3.61 (1.07)</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Perceived weight</td>
<td>1</td>
<td>2.70 (0.40)</td>
<td>4.30 (0.86)</td>
<td>5.39 (1.43)</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Perceived cooling time</td>
<td>1.78 (0.18)</td>
<td>6.22 (0.81)</td>
<td>1.09 (0.08)</td>
<td>4.39 (0.98)</td>
<td>p &lt; 0.001</td>
</tr>
</tbody>
</table>

4.2. Alleviation of RPE, TS and PeSI

The table 3 shows the ratings results of RPE, TS and PeSI wearing and not wearing the cooling vest. EV, PCMV, and ES show a drop in all the variables. FV shows an increase in the three variables. The first section of the job shows a close RPE value across the trials (“severe”- “very severe”), but these ratings change in the second part of the job where the participants wear the cooling method (“somewhat severe”- “very severe”). EV shows the RPE drop to “somewhat severe.” The TS starts for the first section of the job on “slightly hot”- “hot”. EV and PCVM can drop the TS to “neutral”. 
Table 3.
Rating of RPE, TS and PeSI.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ES (Mean±SD)</th>
<th>EV (Mean±SD)</th>
<th>FV (Mean±SD)</th>
<th>PCMV (Mean±SD)</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without</td>
<td>5.83 ± 0.94</td>
<td>5.78 ± 0.95</td>
<td>5.74 ± 0.86</td>
<td>5.48 ± 0.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With</td>
<td>5.52 ± 1.12</td>
<td>4.43 ± 0.90</td>
<td>6.17 ± 1.19</td>
<td>4.52 ± 1.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without</td>
<td>5.74 ± 1.01</td>
<td>5.96 ± 0.77</td>
<td>5.48 ± 0.90</td>
<td>5.70 ± 0.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With</td>
<td>5.30 ± 1.06</td>
<td>4.39 ± 0.72</td>
<td>6.48 ± 0.59</td>
<td>4.57 ± 0.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PeSI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without</td>
<td>6.86 ± 1.24</td>
<td>7.02 ± 1.02</td>
<td>6.60 ± 1.00</td>
<td>6.65 ± 1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With</td>
<td>6.35 ± 1.30</td>
<td>5.04 ± 0.93</td>
<td>7.65 ± 0.80</td>
<td>5.23 ± 1.04</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3. Physical Strain Alleviation (PSA)

Table 4 shows a significant difference between the variables across the cooling methods. EV and PCMV show the most significant improvement in the difference in RPE, TS, and PeSI. EV presents the highest percentage improvement by wearing the cooling vest (23%). FV gives a negative PeSI value, which represents an increase in perceptual heat strain by wearing this product.

Table 4.

| Comparison of ΔRPE, ΔTS, ΔPeSI and PSA between different types of cooling vests. |
|----------|--------------|--------------|--------------|----------------|---|--------------|
| Variable | ES (Mean±SD) | EV (Mean±SD) | FV (Mean±SD) | PCMV (Mean±SD) | F | Significance |
| ΔRPE     | 0.30 ± 0.47  | 1.35 ± 0.57  | -0.43 ± 0.73 | 0.96 ± 0.71    | 33.86 | p < 0.001 |
| ΔTS      | 0.43 ± 0.51  | 1.57 ± 0.66  | -1 ± 0.74    | 1.13 ± 0.55    | 104.8 | p < 0.001 |
| ΔPeSI    | 0.51 ± 0.48  | 1.98 ± 0.72  | -1.05 ± 0.63 | 1.42 ± 0.7     | 120.9 | p < 0.001 |
| PSA      | 5.66 ± 8.98  | 23.31 ± 8.79 | -7.52 ± 11.62| 17.59 ± 13.45 | 36.35 | p < 0.001 |

4.4. Perceived Cooling Time (PCT)

The table 5 displace the PCT for each cooling method. EV presents a average of perceived cooling time of 140 min, followed by PCVM with an average of perceived cooling effect of 71 min. The ES shows an average duration of 11 min. The material of
the ES got dry and rigid, quite faster. And FV present 2 min duration, the miners could not stand more than wearing the vest.

**Table 5.**

Comparison of PCT between different types of cooling vests.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ES</th>
<th>EV</th>
<th>FV</th>
<th>PCMV</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perceived cooling time</td>
<td>1.78 ± 0.42</td>
<td>6.22 ± 0.9</td>
<td>1.09 ± 0.29</td>
<td>4.39 ± 0.99</td>
<td>232.8</td>
<td>p &lt; 0.001</td>
</tr>
</tbody>
</table>

4.5. **Hardhat temperatures**

Every colored hardhat was pair with a white hardhat as a control. The results of the external temperature recorded on the hardhat are shown in figure 3.

The black hardhat absorbed more heat than the other set of colors (15 F more than a white hardhat).

![Figure 3. External temperature of the hardhat.](image)

5. **DISCUSSION**

This study is the first one to be tried on a running mine. The miners were visited at least one day during the day in their regular activities. Since it was too wide to be constantly monitoring their activity, an activity log was handled for each volunteer.
Garment between the body and the cooling method was not controlled. This means that the t-shirt between the direct skin of the volunteer and the cooling method could be cotton or polyester.

Different mining activities preferred different cooling vest. This is because the needs are different and related to the workload and environment conditions. The surveyors cannot carry extra weight in their labor. However, the blaster operators can manage to take additional weight in exchange to complete their stationary work in a “neutral” temperature.

EV gets activated with the breeze. So, it can’t be used in an enclosed area with the limited breeze like in a hot and humid environment underground mine.

The FV works better with a no-so hot temperature. Like inside an office.

Different hardhat color absorbs different quantities of heat. Black color has the property to absorb more heat and can keep the head of the miner hotter for a longer time. The telatems labels differ from the external point to the forehead area for about 3-5 degrees less. However, in the case of the welder, both numbers are the same.

Features like the number of pockets and reflective material can be improved among the cooling methods to enhance the insertion in the mining industry.

6. CONCLUSIONS

Different activities have different needs and have a different preference for cooling technologies. As a whole crew, 70% of the miners prefer EV, 48 % prefer PCMV, 44% prefer ES, and 0% choose FV.

The subjective attributes meet and agree with the alleviation of RPE, TS, PeSI, and PCA.
The colors affect the heat absorption on the hardhat. Black color record a higher temperature among the white, brown, blue, grey, and yellow. White is the coolest one. The telatemp temperature recorder provides an idea of which of the groups experience more heat absorption during the day.

7. ACKNOWLEDGEMENT

United States National Institute of Safety and Health (NIOSH), for providing financial support for this research under ‘Award 200-2014-59953’.

REFERENCES


