Thermal characterisation of the furnace tap floor environment of a platinum group metals smelter

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Dissertation accepted in fulfilment of the requirements for the degree Master of Health Sciences in Occupational Hygiene at the North-West University

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Graduation: June 2025

DECLARATION

I, Danay Stoppel, declare that this research study, *Thermal characterisation of the furnace tap floor environment of a platinum group metals smelter*, is initial work done by myself. This research study serves in the fulfilment of my Master of Health Sciences in Occupational Hygiene at the North-West University in Potchefstroom. This work has not been submitted for examination. The necessary consent of all relevant parties was obtained to conduct the research study, and throughout this dissertation, the required acknowledgement has been given to all referenced material.

ACKNOWLEDGEMENTS

I would like to acknowledge and express appreciation to the following people for their contributions to and involvement with the study:

- The greatest of thanks to my significant other, S.S., for his endless support, patience, love and words of encouragement, during this process and always.
- My mother, for her unconditional support in everything I do.
- Mr. Corné van der Merwe, for his support, optimism and guidance throughout the process and especially his hands-on problem-solving without which this study would not have been possible.
- Prof. Johan du Plessis, for his expert advice and feedback on this dissertation.
- Prof. Stefan Ferreira, for his advice regarding the extrapolation of thermal variables.
- To occupational hygiene and management teams at the smelter (not mentioned here by name due to confidentiality restrictions), for their assistance in arranging the visit and accompanying us through the PGM smelter.
- A special thank you to the furnace tappers at the smelter who so kindly assisted in moving our equipment on the tap floors.

PREFACE

This dissertation was written in article format in accordance with the requirements for the Journal of Occupational and Environmental Hygiene (JOEH). This journal requires that references in the text should be in the form Jones (2018) or Smith and Jones (2018), or Jones et al. (2018) if there are more than two authors. See Chapter 3 for a detailed description of the referencing style. This dissertation is written according to the United Kingdom English spelling convention. This excludes names and references.

The outline of this dissertation is as follows:

- Chapter 1: A general introduction and problem statement related to the thermal characterisation of furnace tap floor environments. This chapter also introduces the aims, objectives and research question of the dissertation.
- Chapter 2: A literature study on topics relevant to this dissertation. This includes an overview of PGM smelting operations, the thermal environment and human thermal balance, the health effects of heat stress and relevant standards and regulations.
- Chapter 3: An article on the topic "Thermal characterisation of the furnace tap floor environment of a platinum group metals smelter" is presented in accordance with the guidelines for *the Journal of Occupational and Environmental Hygiene.*
- Chapter 4: The conclusion of the main findings of the dissertation according to the aims, objectives and research question, along with recommendations, the limitations of this study and potential future studies are discussed.
- Annexure A: The ethics approval letter for this dissertation is provided.
- Annexure B: Proof of language editing of this dissertation is provided.
- Annexure C: The Turnitin® similarity report is provided.

AUTHORS' CONTRIBUTIONS

The contributions of the listed co-authors are given in Table 1-1 below.

Table 1-1: Authors contributions

Author	Contribution
Ms. D.A. Stoppel	• Study design, planning and data collection • Literature research, statistical analysis, interpretation of results and writing of the dissertation
Mr. C.J. van der Merwe	• Supervisor • Assisted with study design, planning, data collection, approval of the protocol, review of the dissertation, documentation of the study and analysis and interpretation of results.
Prof. J.L. du Plessis	• Co-supervisor • Assisted with study planning and design, approval of the protocol, review of the dissertation and documentation of the study

The following is a statement from the supervisors that confirms each individual's role in the study:

I declare that I have approved the article and that my role in the study as indicated above is representative of my actual contribution and that I hereby give my consent that it may be published as part of D.A. Stoppel's MHSc (Occupational Hygiene) dissertation.

Mr. C.J. van der Merwe

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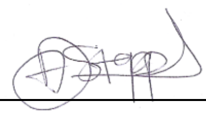

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ABSTRACT

Title: Thermal characterisation of the furnace tap floor environment of a platinum group metals smelter.

Background: South Africa is the leading global producer of platinum group metals (PGMs), a vital industry that relies on high-temperature smelting processes. The smelting of PGM ore occurs in furnaces operating at extreme temperatures of 1350–1600°C, which generate significant radiant heat. Molten materials, released from the furnace during furnace tapping, pose an additional source of radiant heat. This intense thermal environment creates substantial risks of heat stress for workers performing tasks on the furnace tap floors. Despite the critical role these areas play in smelting operations, the thermal environment of furnace tap floors at PGM smelters remains poorly characterised. Understanding these conditions is essential for improving worker safety and informing the design of effective protective equipment.

Objectives: To quantify various environmental variables (heat flux, dry-bulb temperature [DBT], wet-bulb temperature [WBT], globe temperature [GT], relative humidity [RH], wet-bulb globe temperature [WBGT] and air velocity) on the matte and slag tap floors, to assess and compare the spatial variation of the thermal variables within and across the tap floors, and to compare the heat flux and WBGT values to reference values.

Method: Environmental variables were measured across a grid on the matte and slag tap floors at a PGM smelter during normal tapping conditions. Environmental monitoring instruments, including heat stress monitors and a thermal comfort measurement system, were used to quantify heat flux, DBT, WBT, GT, RH and indoor wet-bulb globe temperature ($WBGT_i$) on the tap floors. Contour maps of the thermal variables were generated using Surfer® software to assess spatial variations. Observations were made regarding the tappers' duration of presence in various locations, activity levels and clothing. This information was used to estimate the time-weighted average effective WBGT ($TWA\text{-}WBGT_{eff}$) values according to the ISO 7243 standard for various exposure scenarios. Heat flux exposure at various locations was estimated and compared to the recommended maximum durations for aluminised clothing.

Results: The following mean levels of thermal variables were measured on the slag tap floor: 35.6 ± 3.6°C (DBT), 22.1 ± 1.9°C (WBT), 50 ± 10.4°C (GT), 16.2 ± 5.5% (RH), 29 ± 3.7°C (indoor wet-bulb globe temperature [$WBGT_i$]) and 974 ± 537 W/m² (heat flux). The matte tap floor exhibited the following levels of these variables: 35.8 ± 3.1°C (DBT), 20.8 ± 1.8°C (WBT), 48.5 ± 9.2°C (GT), 11.1 ± 2.3% (RH), 27.8 ± 3.2°C ($WBGT_i$) and 554 ± 458 W/m² (heat flux). Hotspots on the matte tap floor were observed surrounding the active tap-hole and launder, whereas the slag tap floor exhibited a hotspot at the centre front and cooler regions at the sides. A moderate to strong and statistically significant correlation was observed between WBGT and heat flux on both the matte ($r_s(15) = 0.68$, $p = 0.006$) and slag tap floors ($r_s(19) = 0.67$, $p = 0.002$). The TWA-$WBGT_{eff}$ exceeded their respective limits in all scenarios except when only 20 minutes per hour was spent on the tap floors. The heat flux levels at various locations (< 4600 W/m^2) did not exceed the exposure durations since no maximum exposure duration is recommended at this heat flux level.

Conclusion: The matte and slag tap floors present distinct and non-uniform thermal environments with spatially varying conditions. On the matte tap floor, heat is concentrated around the active launder while the slag tap floor presents a more balanced thermal environment, reflecting the difference in tapping practices between the floors. The correlation between heat flux and WBGT suggests future research regarding its potential as a proxy for conventional heat stress metrics. Elevated thermal conditions are present on the tap floors that pose a risk of heat stress to furnace tappers depending on location and exposure duration. More than 20 minutes per hour on the tap floor when wearing an aluminised suit poses a risk of heat stress to furnace tappers. These findings could inform future workplace interventions by identifying high-risk areas and understanding the factors contributing to heat stress, enabling more targeted and effective strategies to protect furnace tappers.

Keywords: furnace tapping, heat flux, heat mapping, heat stress, thermal environment, WBGT

Word count: 684

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LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
CAV	clothing adjustment value
CCOHS	Canadian Centre for Occupational Health and Safety
CFR	Code of Federal Regulations
CSE	Council of Science Editors
DBT	dry-bulb temperature
DoL	Department of Labour (South Africa)
et al.	and others
FEMA	Federal Emergency Management Agency
GT	globe temperature
HR	heart rate
HREC	Health Research Ethics Committee
ILO	International Labour Organization
ISO	International Organization for Standardization
JOEH	Journal of Occupational and Environmental Hygiene
LNG	liquified natural gas
MRT	mean radiant temperature
NFPA	National Fire Protection Association
NIOSH	The National Institute for Occupational Safety and Health
NWU	North-West University
OHHRI	Occupational Hygiene and Health Research Initiative
p	p-value
PCGs	personal cooling garments
PGMs	platinum group metals
PHMSA	Pipeline and Hazardous Materials Safety Administration
PPE	personal protective equipment

PPE	personal protective equipment
RH	relative humidity
r_s	Spearman's correlation coefficient
SD	standard deviation
TLV®	Threshold Limit Values
TWA	time-weighted average
TWA-WBGT	time-weighted average wet-bulb globe temperature
TWA-$WBGT_{eff}$	time-weighted average effective wet-bulb globe temperature
WBGT	wet-bulb globe temperature
$WBGT_{eff}$	effective wet-bulb globe temperature
$WBGT_i$	indoor wet-bulb globe temperature
$WBGT_o$	outdoor wet-bulb globe temperature
WBT	wet-bulb temperature

LIST OF UNITS

%	percentage
°C	degrees Celsius
kg	kilogram
kW/m^2	kilowatts per square metre
m	metres
m/s	metres per second
m^2	square metres
min	minutes
ml	millilitres
s	seconds
W	watts
W/m^2	watts per square metre
μm	micrometer

CHAPTER 1 GENERAL INTRODUCTION

1.1 Background

The platinum group metals (PGMs) consist of six elements – iridium, osmium, platinum, palladium, rhodium, and ruthenium. Due to their catalytic and anti-corrosive properties, PGMs are essential to various industries, including electronics, automotive, medical, chemical, and petroleum (Hughes et al. 2021). South Africa holds more than 80% of the world's PGM reserves, and is the largest global producer of platinum, with an estimated 120 metric tons produced and 181 806 people employed in the PGM mining sector in 2023 (Statista 2024a, 2024b, 2024c).

In the PGM processing chain, smelting is an important separation step following the mining and concentration of PGM ore (Thethwayo 2018). The smelting process involves the application of intense heat to the PGM concentrate to separate valuable metals from gangue minerals (Jones 2005). Smelting produces two molten phases, matte and slag, that are tapped from the smelting furnace at temperature of approximately 1200–1600°C and 1350–1750°C respectively (Eksteen 2011; Jones 2005; Nolet et al. 2022; Shaw et al. 2013; Warner et al. 2007). Consequently, the furnace tapping process exposes workers to significant heat risks.

The human body regulates its thermal balance through metabolic rate adjustments as well as heat loss by conduction, convection, radiation, and evaporation (NIOSH 2016; Osilla et al. 2023). When the environmental heat exceeds the body's ability to dissipate it, heat stress may occur (Foster et al. 2020). Workers are generally at risk of heat stress when working in extreme heat, or when engaged in demanding physical activity (NIOSH 2016). On the furnace tap floor, it is expected that radiant heat from molten materials and the furnace creates a high-temperature environment, elevating the heat stress risk.

Heat stress is influenced by six factors: four environmental (air temperature, humidity, radiation, and air velocity) and two personal (clothing insulation and metabolic load) (NIOSH 2016). Wet-bulb globe temperature (WBGT) is a widely used index for the evaluation of occupational heat stress. International standards such as International Organization for Standardization (ISO) standard 7243 offer a method for the assessment of heat stress based on WBGT and provide reference limits for heat stress exposure (ISO 2017). In South Africa, the Environmental Regulations for Workplaces of 1987, promulgated under the Occupational Health and Safety Act 85 of 1993, require interventions when the one-hour WBGT in a workplace exceeds 30°C (DoL 1987).

There are significant health concerns associated with heat stress, which can range from less severe heat-related ailments like heat rash and cramps to more life-threatening disorders like heat exhaustion and heat stroke (NIOSH 2016). Chronic effects, including kidney disease, DNA damage, and reproductive health issues, are also associated with prolonged heat stress (Alayyannur and Ramdhan 2022; Figa-Talamanca 1992; Venugopal et al. 2018).

Heat transfer to the human body occurs through several mechanisms, including radiation from hot surfaces, convection from surrounding hot air, and conduction through contact with heated materials (Bräuer 2017). Heat flux is the rate of thermal energy flow per unit area and is representative of either radiative, convective or conductive heat transfer, measured in watts per square metre (W/m^2) (Mouritz 2007). In the furnace work environment, radiant heat is considered a greater contributor to heat stress than air temperature, since the furnace poses a significant source of radiant heat (Sharma et al. 2021). Radiation from both the furnace and the molten materials contributes to heat transfer to the body, increasing the risk of heat stress (CCOHS 2024; Giahi et al. 2016). While no formal guidelines specify acceptable heat flux levels for general workplace safety, standards do address heat flux limits related to burn and injury risks, particularly with regard to liquid natural gas (NFPA 2009; PHMSA 2005; Raj 2007). Research also provides guidance on recommended heat flux levels for specific protective clothing ensembles (Heus and Den Hartog 2017).

Heat exposure studies in iron and aluminium smelters have previously been performed (Bernard and Cross 1999; Dang and Dowell 2014; Logan and Bernard 1999; Westcott 2009). These studies investigated the heat stress and heat strain experienced by furnace tappers and cleaners on the matte and slag tap floors in an iron smelter as well as workers in aluminium potrooms (Bernard and Cross 1999; Dang and Dowell 2014; Logan and Bernard 1999, Westcott 2009). Parameters measured or calculated in these studies include WBGT, mean radiant temperature (MRT), dry-bulb temperature (DBT) and relative humidity (RH) as well as heart rate, intra-abdominal core temperature, urine specific gravity, physiological strain index and ratings of perceived exertion. Additionally, Giahi et al. (2016) measured WBGT and MRT around a steel blast furnace to evaluate the effectiveness of control measures. These studies highlighted challenging conditions, with DBTs up to 62°C (Bernard and Cross 1999) and WBGT values up to 49°C (Dang and Dowell 2014).

1.2 Problem statement

The operation of furnace tap floors in PGM smelters presents significant health risks to workers, primarily due to exposure to extreme thermal conditions. Occupational health and safety regulations require employers to protect workers from such hazardous environments to mitigate heat exposure risks. Control measures in such environments include the implementation of industry safety standards, strict adherence to standard operating procedure and well-developed emergency and firefighting plans (Ministry of Steel, Govt. of India. 2019). Radiation barriers, portable reflective shielding or the use of remote-control operations are also recommended but are not always feasible in the furnace environment (ILO 2005). Specialised personal protective clothing is often employed as a control measure in these environments. In many cases however, protective clothing limits evaporative cooling and offers high insulation (Holmér 2006). Thus, striking a balance is difficult: too much insulation can exacerbate heat stress, while insufficient protection might result in serious thermal injury. Additionally, furnace workers might have to perform physically taxing jobs near high-heat furnaces, which elevates both the body's metabolic rate and the heat burden on the body.

To address these challenges, manufacturers are eager to develop specialised protective clothing tailored to the unique thermal environments of furnace tap floors. However, the current understanding of the thermal conditions in the tap floor area remains inadequate. A primary challenge lies in the limited understanding of the precise thermal conditions on tap floors and the extent to which furnace tappers are exposed to these variables. While a study on environmental conditions has been conducted at an iron furnace tap floor (Westcott 2009), there is a significant knowledge gap regarding the environmental specifics of PGM furnace tap floors.

The existing research primarily focuses on heat stress variables such as WBGT, MRT, RH and air velocity, along with heat strain variables such as core body temperature, skin temperature, heart rate, urine specific gravity, body-mass loss and perceived exertion (ISO 2004; Westcott 2009). However, key unknowns remain, such as the identification of local hotspots, airflow patterns, and the degree and directionality of thermal radiation emanating from nearby sources. Additionally, spatial and temporal variability in thermal exposure, the duration of contact with extreme temperatures, and the thermal properties, specifically heat transfer characteristics of surrounding materials further complicate the situation. Therefore, it is important to assess the environmental conditions on furnace tap floors, to inform the design of suitable protective clothing.

1.3 Aim and Objectives

The general aim of this study was to characterise the thermal environment of the furnace tap floors at a South African PGM smelter.

The specific objectives of the study were:

1. To quantify environmental factors, which include heat flux, ambient air temperature, RH WBGT and air velocity on the matte and slag tap floors.
2. To assess and compare the spatial distribution of the measured environmental factors within and across the matte and slag tap floors.
3. To evaluate the environmental heat stress and radiant heat flux levels on the tap floors in relation to reference values.

1.4 Research question

Based on the above objectives, the research question of this study was:

What are the environmental conditions (heat flux, DBT, wet-bulb temperature, globe temperature, RH, WBGT and air velocity) on the tap floors of an electric furnace at a PGM smelter?

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CHAPTER 2 LITERATURE STUDY

2.1 Introduction

This chapter is divided into five sections, namely, an introduction to platinum group metal (PGM) smelting operations and the furnace tapping process, the characteristics of the thermal environment, the health effects of heat stress exposure, published literature on thermal environment characterisation, and occupational health and safety regulations relating to exposure to radiant heat and extreme temperature.

The thermal characterisation of the tap floor environment in smelting operations is particularly important in South Africa, the world's leading producer of PGMs (Schulte 2024). South Africa's PGM smelting operations involve furnaces that operate at extreme temperatures of 1350–1600°C, generating substantial radiant heat, which poses significant heat stress risks to workers (Sharma et al. 2021; Sinisalo and Lundström 2018). Despite the importance of this issue, the thermal characterisation of the tap floor environment in smelting operations is notably under-researched. Existing studies include Westcott (2009) who quantified heat stress on the tap floor of an iron smelter, and Giahi et al. (2014) who quantified wet-bulb globe temperature (WBGT) and mean radiant temperature (MRT) in the area around a blast furnace in a steel production plant (Giahi et al. 2014). Other studies quantifying WBGT have also been performed in aluminium smelter potrooms (Dang and Dowell 2014; Logan and Bernard 1999; Wesdock and Donoghue 2019).

Furthermore, radiant heat flux has mostly been studied in the context of liquified natural gas (LNG), fires or explosions (Raj 2007; Zhang et al. 2019) and firefighting (Lawson et al. 2004; Oliveira et al. 2009; Oliveira et al. 2010), as well as in protective garment performance testing (Kothari and Chakraborty 2016; Naeem et al. 2017; Onofrei et al. 2015; Su et al. 2019).

Given the critical role of PGMs in South Africa's economy, understanding the thermal environment of furnace tap floors is essential for improving worker safety, guiding protective equipment design, and enhancing operational efficiency in the PGM smelting industry. Despite the recognition of these needs, there is a lack of scientific studies characterising the specific thermal environment presented by a PGM furnace tap floor. To the knowledge of the researcher, no studies have aimed to characterise the thermal environment of a PGM smelter furnace tap floor.

2.2 Processing of Platinum Group Metals

The processing of PGMs from mined ore is a multistep process, with each step resulting in a higher concentration of the metal. Depending on the depth and geography of the ore deposit, PGM-containing ores are extracted through either underground or open-pit mining (O'Connor and Alexandrova 2021). Processing of the mined ore typically includes several key stages: comminution, flotation, smelting, and conversion, followed by base metal refining and precious metal refining (Thethwayo 2018).

Comminution**,** defined as the reduction of particle size, involves crushing, milling and gravity separation (Thethwayo 2018). Hereafter, the milled ore is subjected to froth flotation, a process that relies on the difference in hydrophobicity of the minerals and gangue (Bradshaw et al. 2005). During flotation, the ore reacts with reagents in flotation cells to produce a sulphide-rich PGM concentrate (Jones 2005). Due to their hydrophilicity, the valuable minerals adhere to air bubbles and are carried to the surface, while gangue minerals, possessing different hydrophobic properties, do not adhere to the air bubbles (Manono and Corin 2022). The resultant concentrate is dried before being transferred to a furnace where it is smelted (Jones 2005).

2.2.1 PGM smelting operations

Smelting involves the application of heat to concentrate ore in a high-temperature furnace to separate the metal content from the impurities. Two distinct liquid layers form in the furnace due to differences in density: the denser matte layer is composed of iron, nickel, copper, cobalt, sulphur, and PGM-rich sulphides, while the lighter slag layer is rich in silicates and oxides (Jones 2005). From the furnace, the matte is sent to the converter plant where oxygen is passed through it to oxidise iron and sulphur; and reduce the concentration of these elements in the matte (Crundwell et al. 2011; Jones 2005). Slag from the furnace is rapidly cooled through quenching in water (a process known as granulation), before being recycled to recover residual PGMs or discarded (Jones 2005).

Refining is the last step in the processing activity chain and can comprise various sub-steps. The converter matte is cooled and milled before being sent to a base metals refinery (BMR) (Safarzadeh et al. 2018). At the BMR, the converter matte is leached with sulphuric acid to extract copper and nickel (Van Wyk et al. 2021). The product of this process contains a PGM concentrate which is sent to a precious metals refinery where individual PGMs are separated (Crundwell et al. 2011; Jones 2005).

2.2.2 Furnace tapping configuration and practices

Furnace tapping describes the process of releasing the molten material (matte or slag) from the furnace. The material is tapped from the furnace into containers or moulds for further processing or disposal. The holes situated in the furnace wall through which the molten material is tapped, are known as tap-holes. The range of tapping configurations that can be employed in pyrometallurgical operations is diverse. Among these configurations are single tap-hole multiphase tapping and dedicated phase tap-holes, which involve tapping both the matte and slag phases from a single tap-hole or from separate dedicated tap-holes, respectively (Nelson and Hundermark et al. 2016). These configurations determine the specific tapping practices employed in smelters.

Tapping practices may vary from one smelter to another, although the tapping process typically consists of drilling, lancing, tapping, and plugging (Van Beek et al. 2014). The objective is to pierce the solidified matte or slag located in the tap-hole to allow the molten material to flow out of the furnace, before plugging the tap-hole again. Tap-holes are opened by employing either a hydraulic drill, manual oxygen lance or a combination of the two.

The semi-automatic hydraulic drill automatically moves into position in front of the selected tap-hole, while the furnace tapper remotely controls the lowering and drilling action (Van Beek et al. 2014). Oxygen lancing involves the use of a 3-metre-long pipe through which oxygen is fed and ignited to burn through the solidified matte (Van Beek et al. 2014). First introduced in 1901, oxygen lancing allowed for more rapid opening of tap-holes compared to previous manual methods (Dienenthal 2014). Today, oxygen lancing is still used if drilling is not possible or if it is not successful in opening the tap-hole (Dienenthal 2014; Nolet et al. 2022). A 2022 survey of PGM operations indicated that a combination of drilling and lancing is preferred over lancing alone (Nolet et al. 2022). During tapping operations, it is common for two operators to be present on the tap floor: one manoeuvring the lance and the other regulating the oxygen flow (Nolet et al. 2022; Van Beek et al. 2014).

During matte tapping, the molten matte flows through the opened tap-hole into launders and collects in a ladle (Van Beek et al. 2014). Once the ladle is nearly full, or slag is detected in the molten mixture, the tap-hole must be closed by injecting clay into the tap-hole (Nolet et al. 2022; Van Beek et al. 2014). This can be achieved by using a semi-automatic hydraulic mud gun (Pawar 2018) or done manually with stopper rods (Coetzee 2006). The 2022 survey reported that mud guns are preferred over manual plugging in PGM operations (Nolet et al. 2022).

Due to differences in the chemical composition of PGM matte and slag, there are some key distinctions between slag and matte tapping operations. Matte is tapped several times per shift (typically four to five) with a tapping duration ranging from 15 to 30 minutes (Nolet et al. 2022), whereas slag is tapped semi-continuously (Van Beek et al. 2014). The tapped slag is typically granulated in flowing water (Jones 2005).

Smelting operations pose a thermal risk to the health of workers due to the presence of heat from the furnace and molten materials. Tapping is considered one of the most hazardous furnace activities due to exposure to both high temperatures and chemical fumes (Morales et al. 2018). Additionally, workers on the tap floor are also potentially subjected to molten metal splashes, burns, and muscle strains (Nolet et al. 2022).

2.2.3 Tap floor conditions

The furnace types most used for PGM smelting in South Africa are rectangular six-in-line submerged-arc electric furnaces (Jones 2005). The temperatures required to melt the PGM concentrate in these furnaces are typically around 1350°C (Jones 2005). This results in slag operating temperatures from 1350°C to 1750°C, and matte operating temperatures ranging from 1200°C to 1600°C (Eksteen 2011; Jones 2005; Nolet et al. 2022; Shaw et al. 2013; Warner et al. 2007).

It is well-known that significantly higher superheats – temperatures exceeding the melting point of a molten metal – are observed in PGM smelting compared to similar operations such as copper and nickel smelting (Shaw et al. 2013; Van Beek et al. 2014). Slag superheats of 120°C have been reported (Hundermark et al. 2016) while matte superheats of 300–650°C are typical (Nolet et al. 2022; Shaw et al. 2013; Van Beek et al. 2014) in PGM smelting.

As mentioned, radiant heat is an important factor in the tap floor environment since the electric arc furnace and the molten metals pose significant sources of radiant heat (Krishnamurthy et al. 2017; Sharma et al. 2021). Radiant heat emitted from any surface is proportional to the absolute temperature of that surface to the fourth power. This principle is particularly significant when examining high-temperature objects, such as smelting furnaces (Youle 2005).

Westcott (2009) found MRTs of 40.6 ± 9.1°C and 46.2 ± 16.1°C during iron and slag tapping. This study also measured outdoor wet-bulb globe temperature ($WBGT_o$) – WBGT typically measured outdoors under solar load – with recorded values of 21.6°C [1] and 23.2°C during iron and slag tapping, respectively. Giahi et al. (2014) recorded an even greater MRT of 70.4°C and a WBGT of 37.2°C around a steel blast furnace before interventions were installed.

2.3 Thermal environment

The physical environment primarily influences the physiology of an organism by determining the potential for heat exchange between the organism and its surroundings. The thermal environment refers to the conditions that influence the ability of an organism to exchange heat with its surroundings. These factors include temperature, wind speed, radiation, and humidity (Santee and Matthew 2012). Each of these parameters may affect the thermal balance of an organism – individually or in combination – through four heat transfer mechanisms described in the following section.

2.3.1 Thermal balance

In any given environment, the human body attempts to sustain thermal equilibrium by maintaining a deep core body temperature of 37 ± 1°C (NIOSH 2016). If a temperature difference exists between the human body and the surrounding environment, heat will either be transferred to or from the body (Houdas and Ring 2013). The four main mechanisms for the transfer of heat between the human body and the environment are conduction, convection, evaporation and radiation (NIOSH 2016; Santee and Gonzalez 1988; Santee and Matthew 2012). A thermal balance equation has been conceptualised to describe heat exchange between the human body and the environment:

$$S = (M - W) \pm C \pm R \pm K - E , \qquad \text{(Equation 1)}$$

where S is the change in body heat, $(M - W)$ is total metabolism minus external work performed, C is convective heat input or loss, R is radiant heat output or loss, K is conductive input or loss, and E is loss of evaporative heat due to sweating (NIOSH 2016).

Two personal factors that affect heat loss from the body are metabolic rate and clothing insulation (Dhaka et al. 2015), discussed in Sections 2.3.5 and 2.3.6 respectively. The interplay between

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[1] Some authors contend that, due to the unitless nature of the Wet-bulb globe temperature (WBGT) index, the use of the degree Celsius symbol is inappropriate. Conversely, others argue that since all three constituent variables are expressed in degrees Celsius, the index should appropriately reflect the unit of these variables (ACGIH 2023; ISO 2017; NIOSH 2016). In this study, the last-mentioned perspective is adopted.

these factors contribute to the complexity of thermal regulation in the human body. The heat transfer mechanisms and the environmental parameters that influence these mechanisms are discussed in the following sections.

2.3.1.1 Conduction

Conduction is the transfer of heat between two objects when the objects are in physical contact (Wang et al. 2011). Factors that affect the rate of heat loss or gain by conduction include the temperature difference between the skin and the object, the thermal conductivity of the materials involved, and the contact surface area (Youle 2005). The contribution of conduction to thermal balance is usually ignored because conduction is instinctively minimised by humans when discomfort is perceived (Youle 2005). Furthermore, conductive heat loss equates to only a small portion, approximately 3%, of total heat loss in unclothed individuals (Hall 2011).

2.3.1.2 Convection

Convection describes the transfer of heat to or from a surrounding fluid current (Janna 2018). The rate of convective heat transfer depends on the temperature difference between the skin and the fluid, area of exposed skin, as well as the convective heat transfer coefficient, which is influenced by the properties of the fluid (Hundy et al. 2016; Youle 2005). In the case of air, convective heat loss is also influenced by the air flow velocity (Hundy et al. 2016). A distinction can be made between natural (or free) convection and forced convection. In natural convection, heat transfer occurs in still air, whereas forced convection is a result of air moving across the body or vice versa (Youle 2005). In clothed individuals under normal conditions, convection alone can account for approximately 25% of heat loss (Youle 2005). In unclothed individuals, approximately 15% of heat loss is due to the combination of conduction to the surrounding air followed by air convection (Hall 2011; Koop and Tadi 2019).

2.3.1.3 Evaporation

Evaporation is a type of vaporisation in which a liquid is transformed into a gas without boiling (Liu and Wen 2022). Energy is required to transform a liquid into a vapour without a change in temperature (latent heat). In the context of thermal balance, evaporation is the process of water vaporising from the surface of the skin. The energy required for this process is absorbed from the skin, effectively cooling the skin through a process known as evaporative cooling (Etheridge 2010). Evaporation occurs due to vapour pressure differences between the skin and the external environment (Honari and Maibach 2014). The rate of evaporative heat loss depends on ambient temperature, humidity, and air velocity (Youle 2005). Higher ambient temperatures, air movement and lower relative humidity (RH) result in greater heat losses by evaporation (Atmaca and Yigit 2006; Cravello and Ferri 2008; Roghanchi et al. 2016). Moisture may be lost transepidermally or through the respiratory tract by diffusion (insensible water loss), or in the form of sweat actively secreted by sweat glands (water loss in sweat) (Hall 2011; Youle 2005).

Evaporation is the main heat dissipation mechanism in cases where a sufficient water pressure gradient exists (Santee and Matthew 2012). When air temperature exceeds skin temperature, heat is gained rather than lost through radiation and conduction, making evaporation the only effective mechanism for heat loss (Hall 2011; Koop and Tadi 2019). Under typical circumstances, evaporative cooling will account for 30% of heat loss in a sedentary individual wearing light clothing (Youle 2005).

2.3.1.4 Radiation

Radiation describes heat transfer through space by means of electromagnetic waves (Janna 2018). Thermal radiation is a form of electromagnetic radiation that ranges from 0.1 μm to 100 μm. This range includes all visible light and infrared (IR) wavelengths, as well as parts of the ultraviolet (UV) wavelengths (Meseguer et al. 2012). Any object at at a temperature above absolute zero emits thermal radiation to the surrounding environment and radiant heat is exchanged between two objects if a difference in surface temperature exists (Cramer and Jay 2016; Meseguer et al. 2012). The rate of radiant heat transfer between the body and the environment depends on the surface temperatures of the body and of the surrounding objects, the body surface emissivity, clothing insulation and orientation of the body relative to radiating objects (Cramer and Jay 2016). In the human body, vasodilated capillaries near the surface of the skin release heat in the form of thermal radiation (Koop and Tadi 2019). Radiation is a significant heat loss mechanism in the body, accounting for approximately 60% of heat loss in an unclothed person (Hall 2011) and 45% in a clothed person at room temperature (Youle 2005). Conversely, radiant heat sources in the environment, such as furnaces, can also transfer heat to the body and result in heat gain (Sharma et al. 2021).

2.3.2 Environmental factors

Four environmental parameters relate to the above-mentioned heat transfer mechanisms, illustrated simply in Figure 2-1.

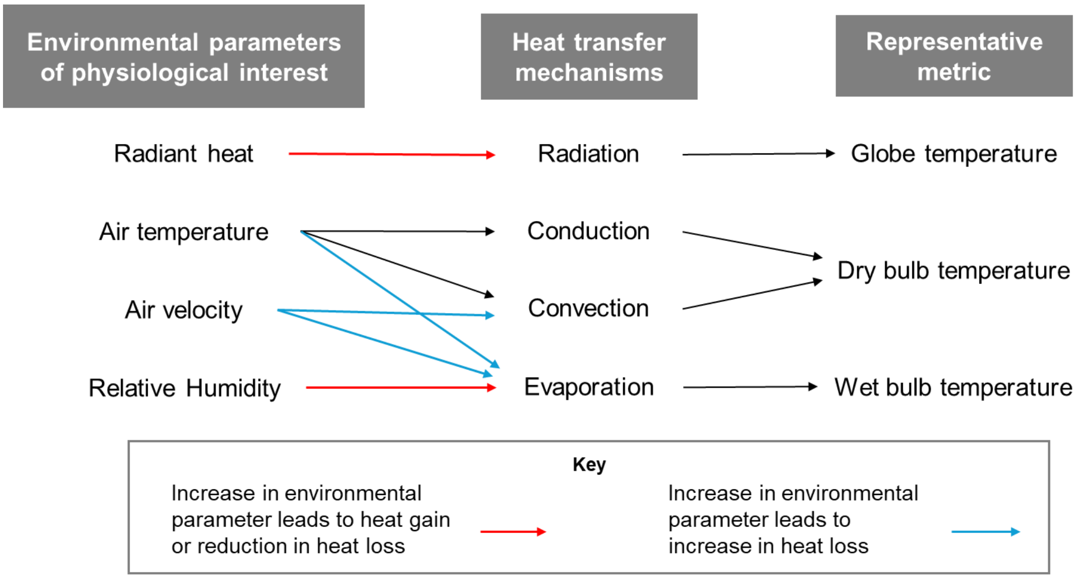

Figure 2-1: Interaction of environmental variables with physiological heat transfer mechanisms (adapted from Roy Choudhury et al. 2011).

2.3.2.1 Air temperature

Air temperature is a measure of the average kinetic energy of air molecules (Coleman and Law 2015) and can be described using different temperature readings, including dry-bulb temperature (DBT), wet-bulb temperature (WBT) and globe temperatures (GT).The DBT is a measure of the ambient air temperature and is obtained by a thermometer exposed to air but shielded from radiation and moisture (Yang et al. 2019). This temperature does not account for the effects of humidity and is an indication of the heat content of the air (Bhatia 2020). In terms of thermal balance, the DBT influences the rate of heat loss by convection, conduction and evaporation (Choudhury et al. 2011). The WBT is measured by a thermometer of which the bulb is covered by a wetted muslin sleeve, exposed to air but shielded from radiation (Legg 2017). The WBT is affected by air movement since greater air movement increases the rate of evaporation resulting in a lower WBT (Vasanth et al. 2023). In addition, increased evaporation and a lower WBT are achieved by a lower RH (Vasanth et al. 2023). The WBT serves as a measure of the lowest temperature the air can attain because of evaporative cooling. (Legg 2017; Razak 2007). The difference between the DBT and WBT is an indication of the relative humidity (Razak 2007) and the temperature gap between the DBT and WBT of the ambient air is what drives evaporative cooling (Amer et al. 2015). The WBT affects thermal balance by influencing heat loss through evaporation (Roy Choudhury et al. 2011). Lastly, GT is measured by a thermometer placed inside a 150 mm diameter copper globe painted matt black (Choudhury et al. 2011). The GT accounts for the effects of temperature, air movement and radiation from surfaces and describes the combined effect of these factors on the human body (Enescu 2017; Choudhury et al. 2011).

Air temperature impacts the heat loss mechanisms of the body. For instance, a higher DBT creates a larger vapour pressure gradient between the skin and air. Therefore, the air has an increased capacity to hold moisture, which results in greater evaporative capacity (Dwyer 2009). Heat loss by convection is dependent on the DBT while heat loss by evaporation depends upon both DBT and WBT (Roy Choudhury et al. 2011).

2.3.2.2 Air velocity

The rate at which air moves is described as air velocity (Skilling and Munro 2016). Air velocity can be measured with anemometers of various types, such as vane anemometers, thermal (hot-wire) anemometers (NIOSH 2016), cup anemometers and kata thermometers (Skilling and Munro 2016). Increased air velocity is a frequently used strategy to reduce heat stress as it results in greater heat dissipation via convection and evaporation. Specifically, an increase of 1 m/s in airspeed can lead to a reduction of 0.2°C to 0.6°C in mean skin temperature in hot and humid environments (Zhou et al. 2023).

2.3.2.3 Humidity

Humidity refers to the amount of water vapour present in the air and is commonly expressed as RH, which is the percentage ratio of the actual amount of water vapour present in the air to the maximum amount of water vapour that the air could hold (Lewis and Chambers 2021). The RH level is indicative of the water vapour pressure, which is crucial since the evaporation rate is dependent on the vapour pressure of the surrounding air. Consequently, the RH of an environment can significantly influence heat loss through evaporation (Sobolewski et al. 2020). In hot environments, where evaporation is the main means of heat dissipation and sweating is required for thermal balance, the effect of humidity becomes particularly pronounced (Berglund 1998). A range of 30–60% is generally considered appropriate for comfort and health (Ness 2022). Conversely, lower RH levels typically enhance total evaporation rates, enhancing the body's ability to cool itself through sweat evaporation (Berglund 1998).

2.3.2.4 Radiant heat

Radiation describes the transmission of energy by electromagnetic waves from either natural radiant heat sources, in the form of solar radiation, or artificial radiant heat sources (NIOSH 2016). It constitutes one of the three modes of heat transfer, alongside conduction and convection. Thermal radiation, or radiant heat, is the emission of electromagnetic waves from any object at a temperature above absolute zero (Blundell and Blundell 2010). Radiant heat transfer is governed by the Stefan Boltzmann law, which states that the emissive power of a blackbody emitter varies with the fourth power of its absolute temperature (Dincer and Siddiqui 2018).

Moreover, radiant heat sources are the primary cause of excessive heat exposure among molten metal workers (Giahi et al. 2016). Human skin is particularly sensitive to changes in radiant heat since it possesses high absorptivity and emissivity (Li 2016). In the context of radiant heat, absorptivity describes the fraction of radiation absorbed by a body, while emissivity is the ratio of the radiant energy emitted by a body to that emitted by a blackbody at the same temperature (De Sousa 2024). Heat accumulation can occur when both ambient air temperature and radiant temperature exceed the average skin surface temperature (Sobolewski et al. 2020).

2.3.3 Heat flux

The terms heat flux and heat flux density are frequently used interchangeably. Heat flux is a vector quantity that describes the rate of heat energy transfer through a given surface, expressed in watts per square metre (W/m^2) (Mouritz 2007). It is a crucial parameter in thermodynamics and heat transfer analysis, as it quantifies the energy flow per unit area. Heat flux can be characterised by its magnitude, direction, spatial distribution, and the nature of the transfer mechanism, which can include conduction, convection, or radiation. Heat flux is typically measured using thermopiles, which evaluate temperature gradients across a surface to determine the rate of energy transfer (Gidik et al. 2016).

Thermal radiation obeys the inverse square law which states that the intensity of radiation from a point source, at a specified distance from the source, is inversely proportional to the square of the distance from the source (Equation 2). This principle implies that as the distance from a radiant heat source increases, the heat flux diminishes rapidly, impacting how heat is experienced in different environments. For instance, this can affect the thermal comfort of individuals working near radiant heat sources, such as furnaces or other industrial equipment. The law is represented by:

$$\boldsymbol{I} \propto \frac{\mathbf{1}}{\boldsymbol{d}^{2}} \,, \qquad \text{(Equation 2)}$$

where I = intensity and d = distance from the source (Talbot-Smith, 2013). In extreme scenarios, such as fires or explosions, heat flux values can be exceptionally high. For instance, heat flux from a fire can reach 175 kW/m^2, and during explosive events, it can reach 1300 kW/m^2, posing serious risks to humans and structures (Ural 2016). Notably, the radiative heat flux component is typically greater than the convective heat flux component at high temperatures, such as those measured during fires and explosions (Ural 2016). Such reference values highlight the importance of understanding heat flux as an occupational hazard in safety and risk management.

2.3.4 Heat stress

Heat stress is defined by the National Institute for Occupational Safety and Health (NIOSH) as the “net heat load to which a worker is exposed from the combined contributions of metabolic heat, environmental factors, and clothing worn which results in an increase in heat storage in the body” (NIOSH 2016). As previously mentioned, heat gain arises from several factors, including environmental conditions, muscular activity (metabolic rate), and the insulating properties of clothing. Among the environmental factors, radiant heat is a significant contributor to heat stress in environments where hot surfaces and materials are present (Sharma et al. 2021).

Heat stress is a well-documented hazard in hot workplaces (Bernard et al. 2000) particularly in industries such as construction, metal processing, and firefighting (CCOHS 2024; Gibb et al. 2024). Employees wearing protective clothing resistant to heat and flames may be especially at risk of heat stress, particularly when the ensemble is impermeable to vapour and airflow, limiting the body’s ability to cool itself through evaporation (Beckett et al. 1986). To assess and manage heat stress effectively, several indices have been developed. Among these, the WBGT index is arguably the most applied measure.

2.3.4.1 WBGT index

Originally developed to prevent heat illness in the U.S. military, the WBGT index is one of the most widely used tools for evaluating heat stress (Golbabaei et al. 2021). It is utilised in various settings, including commercial, agriculture, industrial, and competitive sports environments (Abasilim et al. 2024; Budd 2008; Henderson et al. 2023; Kim and Ham 2024; Parsons 2006; Ridwan 2023) and most recently climatic applications, in investigating the effects of global warming (Ambika et al. 2024).

The index is grounded in human physiology and evaluates the combined effect of environmental conditions and personal factors on human thermal balance (Lemke and Kjellstrom 2012). Four key environmental variables that influence heat transfer are incorporated into the index: air temperature, humidity, radiant heat, and air velocity (Youle 2005). Specific numerical calculations are applied to integrate measurements of DBT, WBT, and GT. A distinction is made between the calculation of WBGT in conditions with and without solar load (ISO 2017).

Without solar load: $WBGT = 0.7\, WBT + 0.3\, GT$ (Equation 3)

With solar load: $WBGT = 0.7\, WBT + 0.2\, GT + 0.1\, DBT$ (Equation 4)

In an environment where solar radiation is present, a higher solar load results in an increased WBGT value (Lemke and Kjellstrom 2012). The radiant heat absorbed by the skin under solar radiation is a significant contributor to the heat stress experienced by an individual (Bröde et al. 2010). Apart from the environmental factors, the metabolic rate and clothing insulation must either be measured by oxygen consumption (in the case of metabolic rate) or estimated using reference values provided by International Organization for Standardization (ISO) standard 7243 (ISO 2017) (see Table 2-3 in Section 2.6 of this chapter).

The index must, however, be used in combination with a recommendation for core body temperature to remain below 38°C, to offer guidance on exposure (Youle 2005). In addition, the WBGT has been critiqued for its limitations, including its lack of sensitivity to low airflow rates and high humidity (Kakaei et al. 2019). Despite these limitations, the WBGT index remains widely used as a screening tool for heat stress due to its convenience, appropriateness, and wide acceptance (d'Ambrosio Alfaano et al. 2014; Golbabaei et al. 2021).

2.3.5 Metabolic rate

Metabolic rate is a measure of the rate of heat production during chemical reactions in the cells of the human body (Hall 2016). This heat production is driven by the consumption of oxygen and the release of carbon dioxide. A person at rest produces approximately 104 W of metabolic heat (Djongyang et al. 2010). Physical activity significantly elevates metabolic rate, with sustained exercise leading to up to a 20-fold increase (Hall 2016). Metabolic rate can be measured directly by assessing oxygen consumption (ISO 8996, 2021) or estimated indirectly based on activity level using reference tables, as found in ISO 7243 (ISO 2017).

2.3.6 The effect of clothing

Clothing plays a crucial role in regulating body temperature and protecting the wearer from environmental hazards. It not only shields against incoming heat but also facilitates the escape of excess metabolic heat (Rossi 2014). Clothing, however, affects the heat loss mechanisms of the body by posing as a heat exchange layer or barrier between the skin and the external environment (Gavin 2003). The presence of this barrier obstructs the exchange of heat and moisture between the body and the environment (Geršak and Marcic 2017; Song et al. 2011). By trapping air adjacent to the skin and decreasing the convectional flow of air currents, a clothing layer decreases the rate of heat loss via conduction and convection (Hall 2011). Depending on the insulative properties of the fabric, evaporation from the surface of the skin may also be impeded (Holmér 2006), since impermeable clothing does not permit evaporative loss, only dry heat loss (radiation, convection, and conduction) (NIOSH 2016).

In industrial settings, clothing often serves to protect the wearer. Molten metal protective clothing or clothing designed for protection against radiant heat and flame, is essential to protect the wearer against hazards ranging from molten metal splash, radiant heat, contact burns, fire, and explosion (Holmes 2000). The design requirements for protective clothing designed to protect against molten metal splashes are specified by the ISO 11612 standard (ISO 2015). This standard specifies requirements for flame-spread behaviour, resistance to convective heat, resistance to radiant heat, resistance to molten aluminium splash and molten iron splash, and contact heat resistance. The thermal insulation provided by clothing is measured in units called "clo", which indicate the degree of insulation a garment offers (Huang and Xu 2006).

Workers dealing with molten metal typically wear a standard clothing assembly that includes cotton coveralls, a tapping suit, a hood, gloves, an apron, and safety boots. Tapping suits comprise of various materials such as Zirpro-treated 100% wool or aluminised fabrics (Coughlan 1992; Bazile 2015). Zirpro treatment involves applying zirconium or titanium salts to woollen fabrics under acidic conditions, to enhance the flame-retardant properties of the wool by depositing a small amount of the flame retardant within the fibres (Benisek 1984). Aluminised furnace tapping suits are often used to prevent the adhesion of molten metal to the fabric in the case of splashes and to reflect radiant heat (AERB 2004). Another study showed that aluminised fabrics offer better thermal protection than non-aluminised fabrics (Hao and Yu 2011; Hrynyk et al. 2012). A reflective aluminium layer, however, reflects the radiant heat from the body back to the skin and encumbers water evaporation due to its low vapour permeability. In a study comparing aluminised and non-aluminised firefighting clothing worn during exercises in radiant heat, it was found that physiological and subjective strains were significantly greater when aluminised clothing was worn (Chou et al. 2011).

Heat dissipation via evaporation is severely limited when workers wear a high level of personal protective equipment (Holmér 1995). Studies have shown that workers performing routine work and wearing vapour-barrier clothing, had higher oral temperatures than workers not wearing the clothing (Mihal 1981). In hot environments, where subjects sweat appreciably, the evaporation of sweat increases the RH of the trapped air layer, causing increased discomfort in the wearer (Geršak and Marcic 2017). The properties of the clothing system that influence thermal balance include thermal resistance (insulation) and evaporative resistance (Song et al. 2011). In addition to restricting heat loss, protective clothing adds weight and restricts the movement of the body, thus increasing the metabolic work necessary to perform a task (Dorman and Havenith 2005). This is especially true for protective clothing designed to protect against molten metal splash (Bazile 2015).

Manufacturers face the challenge of designing clothing that balances thermal protection and thermal comfort (Rossi 2014). In environments with radiant heat, garments should ideally shield the body from surrounding radiant heat (Song et al. 2011) while minimising physiological strain and discomfort, without impairing performance (Holmér 2006). Several factors influence the amount of heat gained from thermal radiation transferred through clothing. These include radiation intensity, the reflective properties of the fabric, the number of clothing layers, and air velocity (Bröde et al. 2006). Additionally, it is crucial to consider the fabric's ability to resist ignition and prevent molten metal from searing through or adhering to it (Horrocks 2005).

2.4 Health effects of heat exposure

In cases where the human body is unable to dissipate heat sufficiently, a rise in core body temperature takes place, resulting in heat-related illnesses. Heat-related illnesses encompass a set of preventable conditions associated with heat exposure, that vary in pathological severity (Becker and Stewart 2011). These conditions may develop quickly and be short-lived (acute) or progress gradually and persist for months or years (chronic).

2.4.1 Acute heat-related disorders

Acute forms of heat-related disorders include heat rash, heat cramps, heat oedema, heat syncope, heat exhaustion and heat stroke. Heat rash or "prickly heat" develops as a result of blocked sweat pores from profuse sweating. This blockage causes sweat to become trapped under the skin, leading to the formation of papules or pustules, typically on the neck, trunk, groin and upper extremities (Gomez 2014). The rash usually resolves when the skin is dried, excess clothing is removed, or the person is transferred to a cooler environment (Gauer and Meyers 2019). Heat cramps, or exercise-associated muscle cramps, are muscle contractions induced by hyponatremia, resulting from inadequate fluid replacement and typically affect the quadriceps, gastrocnemius and abdominals (Bezruchka 2008). Heat oedema describes the accumulation of interstitial fluid in the extremities, resulting in swelling (Scallan et al. 2010). This condition occurs due to cutaneous vasodilation and is resolved by elevation of the extremities or the use of compression stockings (Lugo-Amador et al. 2004).

Heat exhaustion occurs due to significant fluid loss from excessive sweating, leading to a depletion in blood volume. When this volume depletion results in a temporary loss of consciousness, it is known as heat syncope or exercise-associated collapse (Strock et al. 2006). When the core body temperature exceeds 40°C in addition to nervous system dysfunction and the absence of sweating, heat stroke may be diagnosed (Davis 2013). Heat stroke constitutes a medical emergency (Grubenhoff et al. 2007) and may lead to convulsions, delirium, coma and death (Marquardt et al. 2017). The effects of heat stress on organs of the body such as the kidneys and heart, have also been previously documented. An association between heat stress and decreased kidney function (Alayyannur and Ramdhan 2022) as well as an increased risk of acute kidney failure (Flouris et al. 2018) has been demonstrated. Additionally, acute kidney injury has been observed in sugarcane workers (Butler-Dawson et al. 2019) following daily heat stress.

2.4.2 Chronic health effects

In addition to acute health effects, excessive heat exposure has been linked to various chronic effects that can significantly impact overall well-being. Prolonged heat stress can contribute to chronic kidney disease, as highlighted by Alayyannur and Ramdhan (2022). Research has, furthermore, demonstrated that heat exposure can cause DNA damage in lymphocytes (Venugopal et al. 2019), inhibit critical DNA repair mechanisms (Kantidze et al. 2016), and induce further DNA damage (Venugopal et al. 2018). Such genetic impairments can have long-lasting effects on cellular function and overall health. Occupational settings, particularly, reveal alarming trends, for example, impaired spermatogenesis has been reported among workers in the ceramics industry (Figa-Talamanca 1992) and occupational drivers (Vinayakumar 2019), highlighting the reproductive risks associated with thermal stress.

2.5 Published hot occupational environment studies

Table 2-1 summarises the findings of published studies regarding the characterisation of various hot occupational environments. Results from these studies indicate that hot environments can be characterised through environmental data collection. All the studies mentioned in Table 2-1 directly measured, or indirectly estimated WBGT. In addition, other variables measured include MRT, DBT, WBT, GT, RH, radiant heat and wind speed (Bernard and Cross 1999; Dang and Dowell 2014; Giahi et al. 2016; Westcott 2009). While Bernard and Cross (1999) did not directly measure WBGT, they developed a predictive model based on air temperature and humidity at a reference location. Similarly, Logan and Bernard (1999) created a heat stress model using climatic data from a local weather station.

Digital WBGT meters were primarily employed to measure environmental variables. The models utilised included QUESTemp°34 and QUESTemp°36 (Dang and Dowell 2014; Westcott 2009), as well as Casella models (Giahi et al. 2016). Westcott (2009) additionally measured radiant heat

Table 2-1: Summary of literature on hot occupational environments in the metal processing industry.

Setting and country	Environmental variables measured	Position of measurement	Mean variable reading (°C) WBGT	DBT	GT	Reference
Blast furnace of a steel manufacturing plant, Iran	MRT WBGT	Around the furnace	37.2		70.4 (MRT)	Giahi et al. 2016
Aluminium smelter, USA	DBT RH WBGT	Potroom: where workers work and rest	46†	62† 22–62	72†	Bernard and Cross 1999
Aluminium smelter, USA	WBGT (estimated)	Curtain walls, aisleways, and along the catwalks between pots	>ACGIH TLV® (value not stated)			Logan and Bernard 1999
Aluminium smelter potroom workers, USA	Potrooms: WBGT Outdoors: RH, temperature, wind speed	Potrooms: representative of where employees work	28–49	57†	87† Potrooms: ≥ 35.6	Dang and Dowell 2014
Iron smelter, cleaners and tappers of 8-hour and 12-hour shifts, South Africa	WBGT, GT, WBT, DBT, radiant heat, RH	Tap floor: between 2–7 metres from iron and slag launders	19.9 ± 0.4–25.9 ± 7.3*	24.2 ± 1.4–28.5 ± 6.9 *	27.1 ± 3.1–34.2 ± 9.7 *	Westcott 2009

°C – degrees Celsius; WBGT – Wet-bulb globe temperature; DBT – dry-bulb temperature; GT – globe temperature; MRT – mean radiant temperature; RH – relative humidity; ACGIH – American Conference of Governmental Industrial Hygienists; TLV – Threshold Limit Values; WBT – wet-bulb temperature.
* – geometric mean, † – maximum.

using a 150 mm radiation globe. Outdoor conditions were assessed using either WBGT meters (Westcott 2009) or a HOBO® weather station (Onset Computer Corporation, Bourne, MA) (Dang and Dowell 2014). Environmental conditions were generally sampled at various workstations and locations within the workplace, representative of areas where people work and rest. This was the case for the studies of aluminium potrooms (Bernard and Cross 1999; Dang and Dowell 2014; Logan and Bernard 1999). Westcott (2009) measured WBGT at specific distances (2 m, 4–5 m and 7 m) from the matte and slag launders during tapping and cleaning; however, measurements were not taken at the positions of the tappers due to the risk of damage to the instruments.

Data were generally recorded during normal operations or activities with high exposure risks. Giahi et al. (2016) measured variables during normal continual operation and flow of molten material while Logan and Bernard (1999) measured variables during normal cell operations and maintenance, as well as during tapping and handling of molten aluminium. At the iron smelter, data were recorded during tapping and cleaning activities (Westcott 2009).

Several of the studies identified heat stress levels exceeding established limits during certain times. Dang and Dowell (2014) found that all workers except the crane operator, experienced heat stress exceeding both the ACGIH TLV® and NIOSH ceiling limit at various times. Similarly, Bernard and Cross (1999) reported that certain jobs, such as the anode setter and cell operator, also exceeded the NIOSH action limit (24°C for anode setters; 24°C, 25°C and 26°C for cell operators) during specific periods. Furthermore, Logan and Bernard (1999) documented that exposure levels surpassed the TLVs throughout the summer study period. Additionally, Giahi et al. (2016) indicated that the WBGT reference limit of 28°C specified by ISO 7243 was exceeded in workstations located near the furnace. Conversely, Westcott (2009) found that the mean WBGT did not exceed the limits set by ISO 7243. However, the recorded levels for launder cleaners working 12-hour shifts were alarmingly close to this threshold.

2.6 Standards and Regulations

Various national and international standards and regulations exist to guide the management of heat exposure in the workplace. However, specific regulations addressing heat flux in industrial environments, particularly in the smelting industry, are globally limited in legislation.

2.6.1 Heat stress regulations

In South Africa, exposure to heat stress is regulated by the Environmental Regulations for Workplaces 1987 (DoL[2] 1987) under the Occupational Health and Safety Act 85 of 1993. The regulations require action to be taken under certain WBGT conditions (Table 2-2).

ISO 7243 (ISO 2017) is an international standard that offers comprehensive guidelines for assessing heat stress in occupational settings. It details the methodology and instrumentation required for measuring the WBGT and establishes acceptable threshold limits for work in hot environments (Table 2-3). Additionally, the standard includes a calculation method for the time-weighted average (TWA) WBGT to account for variations in the WBGT index over time. It also provides tables for adjusting metabolic rates and clothing factors. The effective wet-bulb globe temperature ($WBGT_{eff}$) is the WBGT value obtained when adjusted for the effects of clothing,

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[2] The Department of Employment and Labour was known as the Department of Labour prior to 2012.

Table 2-2: Environmental Regulations for Workplaces requirements for heat exposure (DoL 1987).

Condition	Action
WBGT index measured over one hour > 30°C	If practicable, take steps to reduce the index to below 30. If not practicable: • have employees certified fit to work • ensure employees are acclimatised • inform employees of the need to partake of 600 ml water every hour • train employees in precautions to avoid heatstroke • have prompt first-aid available

WBGT – wet-bulb globe temperature; °C – degrees Celsius.

Table 2-3: TWA-WBGT$_{eff}$ reference values for different metabolic classes (ISO 2017).

Metabolic rate category	Metabolic rate (W)	WBGT reference limit for acclimatised persons (°C)	WBGT reference limit for unacclimatised persons (°C)
0 (Resting)	115	33	32
1 (Low)	180	30	29
2 (Moderate)	300	28	26
3 (High)	415	26	23
4 (Very high)	520	25	20

Adapted from Table A.1 (ISO 7243, 2017).
W – watts; °C – degrees Celsius; WBGT – wet-bulb globe temperature.

while the time-weighted average effective WBGT (TWA-WBGT$_{eff}$) is the time-weighted measured value adjusted for clothing. Reference values are provided for acclimatised and unacclimatised individuals. An acclimatised person is defined in ISO 7243 (ISO 2017) as a person who has been exposed to hot working conditions for at least a full working week. During this period, the body undergoes physiological adaptations that improve heat tolerance (Pryor et al. 2019).

2.6.2 Heat flux regulations

The environment surrounding a fire is considered a mixed-mode heat transfer environment wherein subjects are exposed to a mixture of convective and radiative heat transfer (Vega et al. 2015). The furnace tap floor can exhibit similar characteristics, necessitating the simultaneous measurement of both convective and radiative heat flux. Existing reference values for heat loads are typically compiled in the context of flammable liquid storage incidents and exposure of emergency responders and firefighters to the fires resulting from these incidents (Heus and Denhartog 2017; Lawson et al. 2004; Oliveira et al. 2009; Oliveira et al. 2010; Raj 2007; Zhang et al. 2019) (Table 2-4).

Table 2-4: Heat flux reference values.

Regulation	Heat flux (kW/m^2)	Criterion type/purpose
NFPA 59A Standard Federal Regulation, 49 CFR part 193	5	Determine hazard distance for LNG fire exposure
Federal Regulation 24 CFR, Section 51.204	1.42	Administrative relief from regulations if mitigation measures are provided

kW/m^2 – kilowatts per square metre; NFPA – National Fire Protection Association; LNG – liquified natural gas; CFR – Code of Federal Regulations.

Table 2-5: Reference exposure limits for heat load of three clothing types (Heus and Den Hartog 2017; Heus et al. 2022).

Heat load (kW/m^2)	Duration						Reference
	Standing posture			Walking posture			
	Operator (long-sleeve)	Firefighter	Aluminised	Operator (long-sleeve)	Firefighter	Aluminised	
1.5	5 min						Heus et al. 2022
2	3 min						
3	88	430 s	No limit	33 s	105 s*	No limit	Heus and Den Hartog 2017
4.6	58	168 s	No limit	20 s	173 s	160 s	
6.3	–	120 s	No limit	–	73 s	250 s	
10	–	88 s	70 s	–	60 s	85 s	

kW/m^2 – kilowatts per square metre; s – seconds.
*value disregarded by authors; – no measurements.

Heus and Denhartog (2017) have, however, investigated the maximum safe duration of wear of three clothing types, namely operator clothing, firefighter clothing and aluminised clothing, using a thermal manikin. The authors suggested safe heat flux levels for each type of attire based on their results (Table 2-5). It was concluded that operators' clothing could be safely used up to 1.5 kW/m^2, and firefighters' clothing up to 3.0 kW/m^2, with firefighter clothing being tolerable for up to 4.6 kW/m^2 for almost 3 minutes. Levels above 4.6 kW/m^2, however, require the wearing of aluminised clothing. No maximum time limit was established at 3 kW/m^2 when the aluminised suit was worn (Heus & Denhartog 2017).

Physiological indicators may also present a useful measure of exposure times. Pain is felt by a subject when skin temperature rises above 44°C. The physiological effects of exposure to radiant heat on bare skin have been established in terms of the duration of exposure required to produce pain or second-degree burns (Table 2-6) (FEMA et al. 1988).

Table 2-6: Time for physiological effects on bare skin following thermal radiation according to Handbook of Chemical Hazard Analysis Procedures (FEMA et al. 1988).

Radiation Intensity (kW/m^2)	Time for severe pain (s)	Time for second-degree burns (s)
1	115	663
2	45	187
3	27	92
4	18	57
5	13	40
6	11	30
8	7	20
10	5	14
12	4	11

kW/m^2 – kilowatts per square metre; s – seconds

Despite an extensive review of local and international legislation, standards and guidelines, no heat flux limit specifically applicable to the smelter environment could be identified.

2.7 Conclusion

High temperature and thermal radiation levels have been recorded in the smelter environment of the aluminium, steel and iron industries (Bernard and Cross 1999; Dang and Dowell 2014; Giahi et al. 2016; Logan and Bernard, 1999; Westcott 2009). Consequently, it is anticipated that similar high temperatures and radiant heat levels may arise in the PGM smelting environment as well, specifically on the tap floor due to the presence of molten materials and high-temperature electric furnaces. Additionally, protective clothing can obstruct the body's heat loss mechanisms, contributing to heat stress alongside factors like metabolic rate and environmental conditions. Excessive heat exposure can result in both acute and chronic health effects, ranging from heat rash to heat stroke.

Guidelines for heat stress, measured by WBGT, are established in local regulations and international standards, outlining working conditions that are not detrimental to health and safety. However, guidelines for heat flux are less well-defined. Studies have quantified thermal variables in the metal processing industry through environmental data collection, revealing heat stress levels that exceed established reference limits.

2.8 References

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CHAPTER 3 ARTICLE

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For examination, the authors felt it necessary to explain sections such as Methods and Discussion in more detail and that readability will be enhanced with placement of tables and figures within the text. After examination and before submission of the manuscript (article) to the journal, this will be amended.

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Structure of paper: A technical manuscript must report a scientific investigation and provide the following, in detail: an introduction, objectives/hypothesis, description of the methods, description of data analyses performed, results obtained, synthesis of the data with limitations, and conclusions supported by the evidence generated. Additionally, it should include recommendations, acknowledgements and a data availability statement.

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Examples:

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Thermal characterisation of the tap floor environment of a platinum group metals smelter

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3.1 ABSTRACT

Background: Workers performing furnace tapping tasks in hot metal environments are at a high risk of heat stress due to exposure to extreme thermal conditions. The thermal environment of furnace tap floors, particularly at a platinum group metals (PGM) smelter, remains poorly characterised, despite its importance for operator safety and protective equipment design.

Objectives: To quantify thermal environmental factors on the matte and slag tap floors, to assess and compare the spatial distribution of the measured environmental factors within and across the matte and slag tap floors, and to evaluate the environmental heat stress and radiant heat flux levels on the tap floor in relation to reference values.

Method: Thermal variables, including heat flux, wet-bulb temperature (WBT), dry-bulb temperature (DBT), globe temperature (GT), relative humidity (RH) and indoor wet-bulb globe temperature ($WBGT_i$) were measured across a grid on the tap floors at a PGM smelter during normal tapping conditions. Contour maps were generated to visualise spatial variations. Time-weighted average effective WBGT ($TWA\text{-}WBGT_{eff}$) was estimated according to International Standards Organization (ISO) standard 7243, for various exposure scenarios. Heat flux levels were considered in terms of recommended maximum durations for aluminised clothing.

Results: The thermal environment of the furnace tap floors was characterised by significant spatial variability. Mean and maximum levels of heat flux on the matte tap floor were 974 ± 537 watts per square metre (W/m²) and 2484 W/m² respectively, while on the matte tap floor these were 554 ± 458 W/m² and 1342 W/m² respectively. Mean and maximum $WBGT_i$ values of 29 ± 3.7°C and 38.2°C, respectively, on the slag tap floor, and 27.8 ± 3.2°C and 34.23°C, respectively, on the matte tap floor were recorded. Spearman's correlation revealed a moderate to strong positive relationship between heat flux and WBGT on both the matte ($r_s(15) = 0.68$, p =

0.006) and slag tap floors ($r_s(19) = 0.67$, $p = 0.002$). Effective WBGT values exceeded ISO 7243 (2017) limits in most scenarios, suggesting a heightened risk of heat stress, on both the slag and matte tap floor. In contrast, heat flux measurements remained below maximum allowable exposure durations, reflecting the differing implications of these metrics.

Conclusions: The matte and slag tap floors present distinct and non-uniform thermal environments. The slag tap floor exhibited more symmetric thermal conditions from left to right, as it typically uses three active tap-holes, while only one tap-hole is used on the matte tap floor at a time. A statistically significant correlation of heat flux with WBGT suggests that heat flux may be further investigated as a proxy for traditional heat stress measurement. Furnace tappers at the PGM smelter wearing aluminised clothing are susceptible to developing heat stress if more than 20 minutes of any hour is spent on the tapping floor. These findings emphasise the importance of tailoring personal protective equipment (PPE) to balance radiant heat protection and thermal comfort.

Keywords: furnace tapping, heat flux, heat mapping, heat stress, thermal environment, WBGT

Words: 487

3.2 INTRODUCTION

The platinum group metals (PGMs) comprise platinum, rhodium, ruthenium, palladium, osmium and iridium. South Africa's Bushveld complex contains approximately 75% of global platinum deposits and South Africa is the leading producer of platinum, having produced an estimated 120 metric tons in 2023 (SFA Oxford 2024; Statista 2004).

The processing of PGM ores involves several stages, including comminution, flotation, smelting, converting and refining. Mined ore is crushed, milled and treated in gravity separators and flotation cells, to separate the material based on weight and hydrophobicity (Bradshaw et al. 2005; Thethwayo 2018). The resultant flotation concentrate undergoes smelting, during which it is heated to high temperatures in a furnace to separate the silicates (containing gangue minerals) and sulphides (containing valuable PGMs). This process results in two immiscible molten layers: a matte layer rich in PGMs and sulphides, and a slag layer composed of silicates and oxides (Eksteen et al. 2011). The molten layers are released from the furnace through tap-holes in the furnace wall, a process referred to as furnace tapping (Thethwayo 2018). The drilling of a tap-hole is typically carried out by a semi-automatic drill, but worker intervention in the form of oxygen lancing may be required if drilling is either not possible or not successful (Dienenthal 2014; Nolet et al. 2022).

The tapping process begins when a hydraulic mud gun and drill assembly is positioned in front of the designated tap-hole. The clay plug sealing the tap-hole is drilled out using the remotely operated drill controlled by an operator in the tapping cabin. In most cases, drilling effectively opens the tap-hole, allowing the molten matte or slag to flow into the launders. If the tap-hole is not fully opened by drilling alone, the operator may manually use an oxygen lance to penetrate any remaining solidified material. Slag is tapped on a semi-continuous basis from all three tap-holes, while matte is tapped from only one tap-hole at a time. One matte tap typically lasts between 15 and 30 minutes (Nolet et al. 2022). After tapping, the tap-hole is closed by using the mud gun to plug the hole with clay (Pawar 2018).

PGM furnaces operate at very high temperatures, 1350–1600°C, considerably higher temperatures than seen in copper and nickel sulphide smelting (Jones 2005; Shaw et al. 2012). Tasks performed on the tap floor, such as oxygen lancing, expose workers to significant thermal risks due to their proximity to the furnace and molten materials, increasing the likelihood of heat stress.

Heat stress is an occupational hazard in smelting environments. While investigations typically focus on personal exposure, little attention has been given to characterising the workplace environment itself. In non-uniform thermal environments where workers are highly mobile, environmental characterisation may be essential, as exposure to excessive heat may cause severe adverse health effects. Heat stress can cause heat rash, cramps, oedema, and syncope (Bezruchka 2008; Gomez 2014; Scallan et al. 2010; Strock et al. 2006) and if left untreated, can escalate to life-threatening heat stroke (Davis 2013).

The wet-bulb globe temperature (WBGT) is a widely used metric for assessing heat stress, representing factors like air temperature, humidity, radiation, and air velocity by combining three parameters namely dry-bulb temperature (DBT), wet-bulb temperature (WBT) and globe temperature (GT). Heat stress reference limits provided by International standards Organization (ISO) standard 7243 (ISO 2017) and the American Conference of Governmental Industrial Hygienists (ACGIH 2023) consider WBGT alongside metabolic rate and clothing adjustment values (CAVs).

Heat flux, expressed in watts per square metre (W/m^2), quantifies the rate of heat energy transfer through a given surface (Mouritz 2007). Heat flux can occur via three primary mechanisms: radiant, convective, or conductive transfer. Radiant heat flux arises from electromagnetic radiation emitted by hot surfaces, which can significantly impact workers near high-temperature sources (Miller 2012). Heus & Denhartog (2017) recommends various maximum duration limits for different protective ensembles, including operator clothing, firefighter clothing and aluminised clothing, at certain heat flux levels. The researchers found that levels above 4.6 kW/m^2 require the use of aluminised clothing.

Westcott (2009) investigated heat stress and strain on the tap floor of a South African iron smelter, reporting warm to hot environmental conditions. The study recorded a maximum GT of 53°C and a DBT of 41°C, with maximum – but not mean – WBGT values exceeding the ISO 7243 (2017) limits (26°C for cleaners and 28°C for tappers). Similar conditions are likely to occur on PGM smelter tap floors**,** given the comparable nature of these environments. However, studies specifically characterising the thermal environment of furnace tap floors at PGM smelters remain lacking. Furthermore, the thermal discomfort caused by existing PPE necessitates heat exposure data to inform the design of more effective protective garments.

This study aims to quantify environmental factors, (which include heat flux, DBT, WBT, GT, relative humidity [RH], indoor wet-bulb globe temperature [$WBGT_i$] and air velocity) on the matte and slag tap floors of a PGM smelter, to assess and compare the spatial distribution of the measured environmental factors within and across the matte and slag tap floors and to evaluate the environmental heat stress and radiant heat flux levels on the tap floors in relation to reference values.

3.3 MATERIALS AND METHODS

The study was performed on the furnace tap floor of a PGM smelter in South Africa. Each tap floor, approximately 70 m^2, was shielded from direct solar radiation but open to the outdoors on one or more sides. On the matte tap floor, molten matte is tapped from either one of the three tap-holes in the furnace end wall, from where it flows into launders which are positioned parallel to one another. On the slag tap floor, molten slag is tapped from one, two or three tap-holes at any given time. From each tap-hole, the slag flows into diverging launders and is granulated further downstream by a stream of water. Tapping operations included three furnace tap-holes (referred to as east, centre, and west) on each floor. On the slag tap floor one or more tap-holes would periodically close and require reopening by hydraulic drilling or manual oxygen lancing. On the matte tap floor, measurements were taken during the tapping of the west (right-hand side) tap-hole.

3.3.1 Environmental monitoring and data collection strategy

A grid measuring 4.2 m by 10 m, divided into 21 squares each measuring 1.4 m by 1.43 m, was marked on the tap floor using chalk. Measurements were taken at the centre of each square on the grid, where feasible. A QUESTemp° 36 heat stress monitor (TSI® Incorporated, Shoreview, Minnesota, USA) and a TCOMSYS01 Hot Cube thermal comfort measurement system (Hukseflux Thermal Sensors, Delft, Netherlands) were mounted on a trolley at heights of 1.6 m and 1 m, respectively. The instruments used for environmental monitoring in the selected area are indicated in Table 3-1. The Hot Cube system consists of an aluminium cube equipped with five heat flux sensors mounted on its front, right, back, top, and left planes. The trolley was moved between measurement points by a worker upon the researchers' request. Measurements were taken for a minimum of one minute at each location, with the frontal heat flux sensor of the Hot Cube consistently facing the furnace end wall.

On the slag tap floor, where the launders descend underground, they are covered by grids placed in the floor surface. The instruments were not placed above these grids to avoid steam damage. In these instances, the instrument trolley was placed as close as possible to the marked location. On the slag tap floor, efforts were also made to take measurements when all three tap-holes were simultaneously open. However, due to periodic closures, readings at seven locations were taken when only two of the three holes were open. Locations 16 and 17, as well as 18 to 19 were combined into two points respectively, due to their proximity as a result of the diverging nature of the launders. On the matte tap floor, measurements could not be taken at six locations due to time constraints.

Two additional QUESTemp° (TSI® Incorporated, Shoreview, Minnesota, USA) heat stress monitors were placed in other locations, one outdoors (under solar radiation) and another in an open area on the transformer floor (undercover, without solar radiation) to assess the environmental conditions in these areas. In addition, a Kestrel heat stress tracker (Kestrel® Instruments, Boothwyn, Pennsylvania, USA) was placed outdoors to obtain additional meteorological information and a VelociCalc® air velocity meter (TSI® Incorporated, Shoreview, Minnesota, USA) was used to determine air velocity on the tap floors.

Table 3-1: Environmental thermal monitoring instrumentation.

Instrument	Manufacturer	Location	Variables measured
QUESTemp° 34 area heat stress monitor	TSI® Incorporated	Outdoors	DBT, WBT, GT, RH, $WBGT_o$
QUESTemp° 34 area heat stress monitor	TSI® Incorporated	Transformer floor	DBT, WBT, GT, RH, $WBGT_i$
QUESTemp° 36 area heat stress monitor	TSI® Incorporated	Tap floors	DBT, WBT, GT, RH, $WBGT_i$
TCOMSYS01 Hot Cube thermal comfort measuring system	Hukseflux Thermal Sensors	Tap floors	Combined radiative and convective heat flux (5 directions), RH, ambient air temperature, heating power for stabilisation, TCOM01 body temperature
Kestrel 5400CL heat stress tracker	Kestrel® Instruments	Outdoors	Wind speed, temperature, wind chill, RH, heat stress index, dewpoint temperature, WBT, station pressure, barometric pressure, altitude, density altitude, wind direction, crosswind, headwind/tailwind
VelociCalc® air velocity meter 9515	TSI® Incorporated	Tap floors	Air velocity

DBT – dry-bulb temperature; WBT – wet-bulb temperature; GT – globe temperature; RH – relative humidity; $WBGT_o$ – outdoor wet-bulb globe temperature; $WBGT_i$ – indoor wet-bulb globe temperature.

3.3.2 Tapper WBGT estimation

Two tappers were present on the slag tap floor, while one tapper was on the matte tap floor during data collection. Observations of tapper behaviour were conducted during the measurement period. Researchers noted movement patterns, tasks performed, frequently occupied locations, and the type and duration of protective clothing worn at each location. Furnace tappers frequented three general areas to perform tasks on the tap floors: 1) inside the tapping cabin, either sitting down to rest or standing at the control panel to operate the drill or mud gun, 2) near the back of the tap floor, walking across the tap floor or taking temperature readings of the matte or slag, 3) very near the tap-hole, inspecting the tap-hole or lancing the tap-hole.

Furnace tappers wore standard cotton coveralls underneath black Zirpro-treated woollen tapping suits (coveralls). Zirpro flame retardant treatment for wool fabrics was developed around 1970 and uses metal complexes, such as zirconium, under acidic conditions to treat wool (Benisek 1984). However, some tappers wore Charnaud® (Charnaud ® & Co (Pty) Ltd) aluminised jackets and pants over standard cotton coveralls since the smelter was in the process of transitioning to these aluminised suits at the time of data collection. Protective accessories worn included hard hats, safety glasses, gloves, safety boots and aluminised hoods (when wearing aluminised suits). The level of clothing worn by tappers varied based on the location and activity of the tapper. When outside the cabin, the woollen or aluminised suits were donned, without the aluminised hood. The hood was only seen donned once during lancing, during the pre-visit to the smelter. During the data collection period, no tappers were observed wearing the aluminised hoods. When entering the cabin, some of the tappers pulled down the woollen suit to the level of the waist or in the case of the aluminised ensemble, the jacket was taken off. For this study, the clothing ensembles worn by tappers were classified based on ISO standard 7243

(Table F.1) as follows: Zirpro wool coveralls – “double layer woven clothing” (CAV of 3), aluminised jacket and pants ensemble – “vapour-barrier over cloth overalls, without hood” (CAV of 12) with the hood added for the location at the front of the tap floor (CAV +1). Clothing worn inside the tapping cabin ware classified as “cloth coveralls” (CAV 0) since no specifications regarding lower-body-only wear of these garments are given.

Representative time-weighted average WBGT (TWA-WBGT) levels were calculated for the three high-activity tapper locations according to formula (4) of ISO 7243:

$$\overline{p} = \frac{(p_1 \times t_1) + (p_2 \times t_2) + \cdots + (p_n \times t_n)}{t_1 + t_2 + \cdots + t_n} \qquad \text{(Equation 5)}$$

Where p_1, p_2, ... p_n is the level of the parameter (WBGT in this case) obtained during time t_1, t_2, ... t_n; and $t_1 + t_2 + ... = T = 1$ h.

The effective wet-bulb globe temperature ($WBGT_{eff}$) is the WBGT value obtained when adjusted for the effects of clothing while the time-weighted average effective WBGT (TWA-$WBGT_{eff}$) is the time-weighted measured value adjusted for clothing (ISO 2017). The TWA-$WBGT_{eff}$ values for various scenarios were estimated based on possible tapper exposure scenarios according to:

$$WBGT_{eff} = WBGT + CAV \qquad \text{(Equation 6)}$$

The metabolic rate at each of these locations was estimated based on Table E.1 of ISO 7243 and a mean metabolic rate for each scenario was calculated using Equation 5. Reference limits were obtained by linear interpolation in Table A.1 of ISO 7243, based on the estimated TWA metabolic rates. Values used for the WBGT analysis included measurements made when some tap-holes were closed to render a more realistic estimation of WBGT exposure.

3.3.3 Data analysis and statistics

Descriptive statistics for the environmental data were performed using GraphPad Prism 10.0 (GraphPad Software, San Diego, California) and included calculation of the mean, standard deviation, and minimum and maximum values. For each location with multiple one-minute averages, the mean of these values was used to represent that location's measurement.

Contour maps visualising heat flux and WBGT distributions across the tap floors were generated using Surfer® 28.1.248 (Golden Software, LLC, Golden, Colorado). Measured data were interpolated (matte tap floor) and extrapolated (both floors) using this software to obtain missing measurements within and in front of the measured grid and values at unmeasured locations. The selected gridding method for all contour maps was local polynomial. This gridding method fits a local polynomial to each grid node using weighted least squares, based on the neighbouring data. In some cases, the left or right heat flux sensors detected greater heat flux levels than the frontal sensor. For the generation of the contour maps the greatest heat flux at any of the five sensors was used.

Non-parametric tests were used because the data were not normally distributed, as verified by the Shapiro-Wilk test. A Spearman's rank-order correlation was conducted to assess the relationship between heat flux and other variables, including WBGT, DB, WBT and GT, on the matte and slag tap floors respectively.

Some measurements near the active tap-hole on the matte tap floor were unavailable due to time constraints, resulting in missing data for seven locations. This limitation likely influenced the comparison between the two tap floors, as these areas are expected to exhibit higher environmental heat stress levels.

All values measured by the Hot Cube on the matte tap floor were adjusted by two minutes to account for instrumentation lag. Heat flux levels were compared to recommended maximum exposure durations (no time limit up to 4.6 kW/m^2; 5 minutes at 6.3 kW/m^2 and 70 seconds at 10 kW/m^2) established by Heus and Denhartog (2017) for aluminised clothing.

3.3.4 Ethical considerations

Ethical approval for this study was obtained from the Health Research Ethics Committee (HREC) of the North-West University (NWU-00193-23-A1). This study did not involve any human participants and data were exclusively collected from environmental monitoring equipment placed in the designated area and observations made by the researchers concerning the tapping process and job activities performed by the furnace tappers.

3.4 RESULTS

Data collection was conducted in autumn (late April) and conditions on the day of measurements were sunny and cloudless. A mean DBT of 29.5°C ± 1.0°C and $WBGT_o$ of 21.9 ± 2.1°C were recorded outdoors.

3.4.1 Environmental conditions on the tap floors

The maximum, minimum and mean values of heat stress variables are indicated in Table 3-2. Measurements with tap-holes closed on the slag tap floor were included.

3.4.1.1 Heat flux

Matte temperatures during the tap were reported as 1480–1481°C and the tap duration was approximately 25 minutes. The distribution of mean heat flux levels on the matte tap floor is indicated in Figure 3-1. The measurement grid extended from locations 1 to 21 on each tap floor, with locations 15–21 measured closest to the furnace end wall.

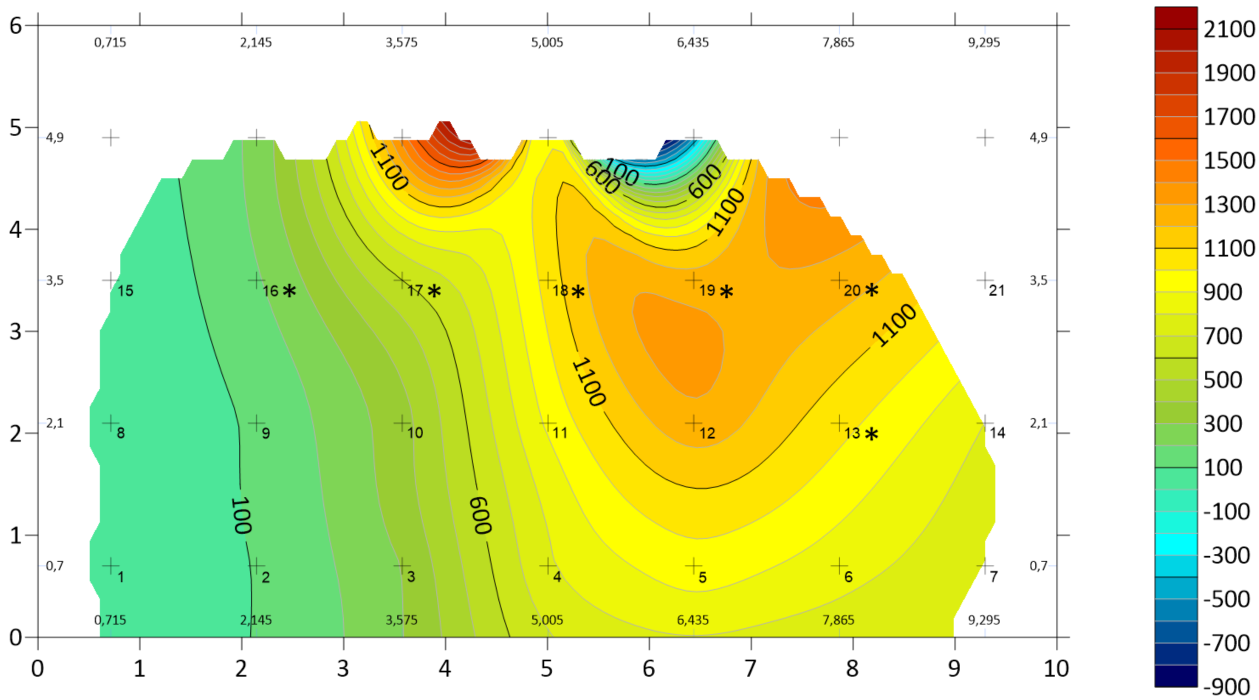
Table 3-2: Environmental conditions on the matte and slag tap floor.

	Matte tap floor	Location measured*	Slag tap floor	Location measured*
Dry-bulb temperature (°C)				
Mean ± SD	35.8 ± 3.1		35.6 ± 3.6	
Maximum	39.9	21	43	5; 18–19
Minimum	29.6	1	29.2	14
Wet-bulb temperature (°C)				
Mean ± SD	20.8 ± 1.8		22.1 ± 1.9	
Maximum	24.5	9	27.8	5
Minimum	16.7	1	16.3	14
Globe temperature (°C)				
Mean ± SD	48.5 ± 9.2		50 ± 10.4	
Maximum	67.9	21	75.3	18–19
Minimum	32.1	1	30.1	14
Relative humidity (%)				
Mean ± SD	11.1 ± 2.3		16.2 ± 5.5	
Maximum	17	1	44	14
Minimum	9	8–12; 14–15; 21	8	20; 21
$WBGT_i$ (°C)				
Mean ± SD	27.8 ± 3.2		29 ± 3.7	
Maximum	34.2	21	38.2	18–19
Minimum	21.0	1	20.4	14

°C – degrees Celsius; SD – standard deviation; $WBGT_i$ – indoor wet-bulb globe temperature.
* referring to the position within the measurement grid on the tap floor.

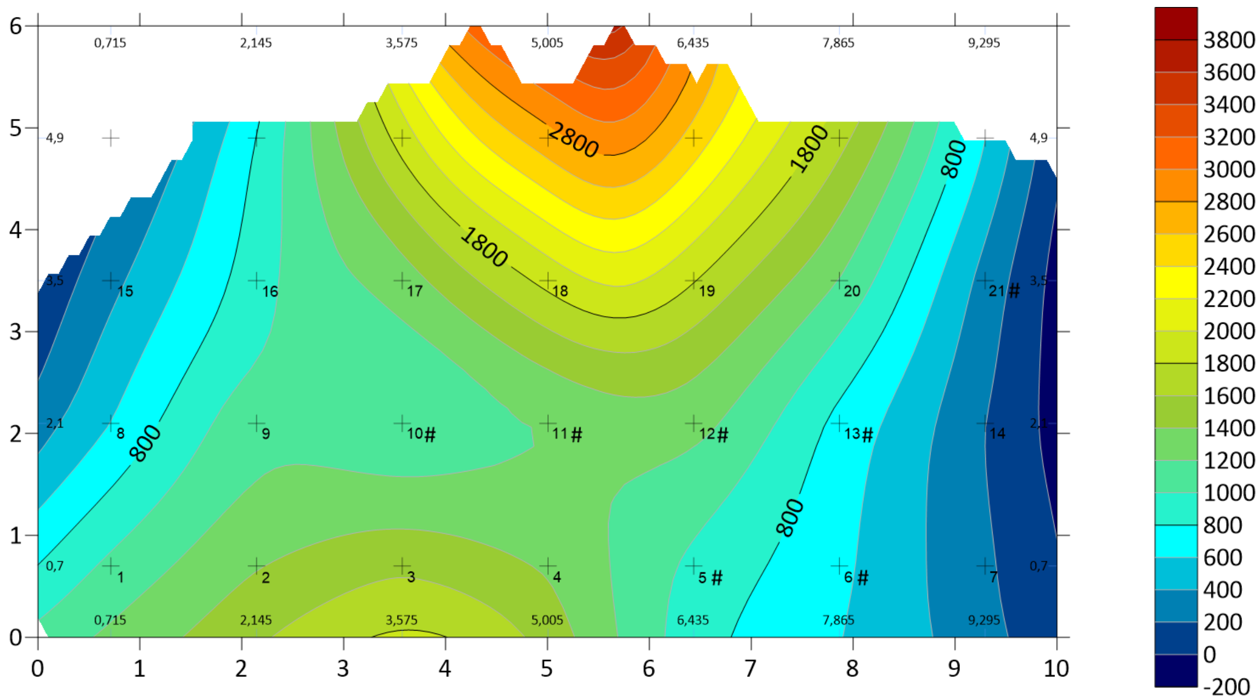
Slag was tapped continuously, and the flow of molten slag was only interrupted when the tap-holes closed up, the drill bit melted off or the launder was scraped. Slag temperatures measured by the tappers during this time ranged from 1547–1587°C. The distribution of mean heat flux levels on the slag tap floor, where all measurements were included regardless of tap-hole status, is indicated in Figure 3-2. Figure 3-3 indicates the distribution of mean heat flux on the slag tap floor when the values obtained during the closure of a tap-hole are excluded from the calculations.

The highest one-minute mean heat flux recorded during the matte tapping period was 1342 W/m^2 at location 12. The mean heat flux across the matte tap floor grid was 554 ± 458 W/m^2. The maximum one-minute mean heat flux recorded on the slag tap floor was 2484 W/m^2 at location 18–19. The mean heat flux across the entire slag tap floor was 974 ± 537 W/m^2. The highest projected heat flux values obtained via extrapolation were 2091 W/m^2 on the matte tap floor and 3651 W/m^2 on the slag tap floor.



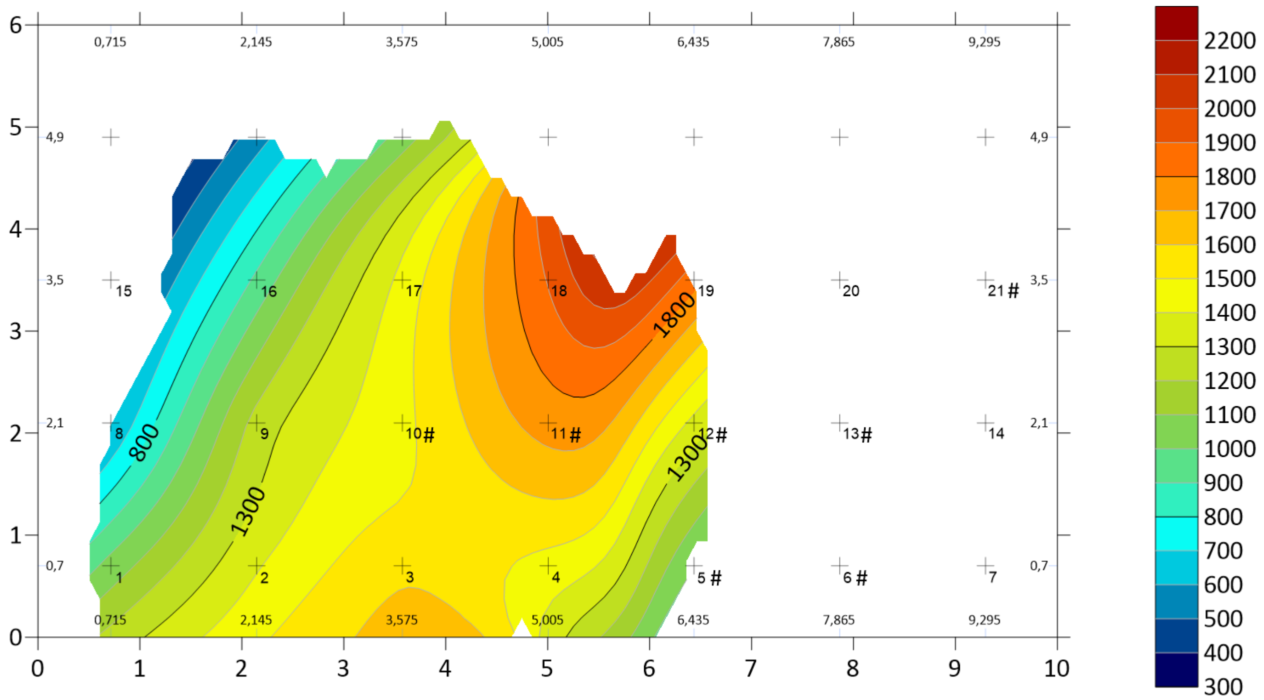
+ measured locations # locations with closure of a tap-hole (Top of map indicates furnace end wall.)

Figure 3-1: Contour map of mean heat flux levels (W/m^2) on matte tap floor.



+ measured locations # locations with closure of a tap-hole (Top of map indicates furnace end wall.)

Figure 3-2: Contour map of mean heat flux levels (W/m^2) on slag tap floor (all locations).



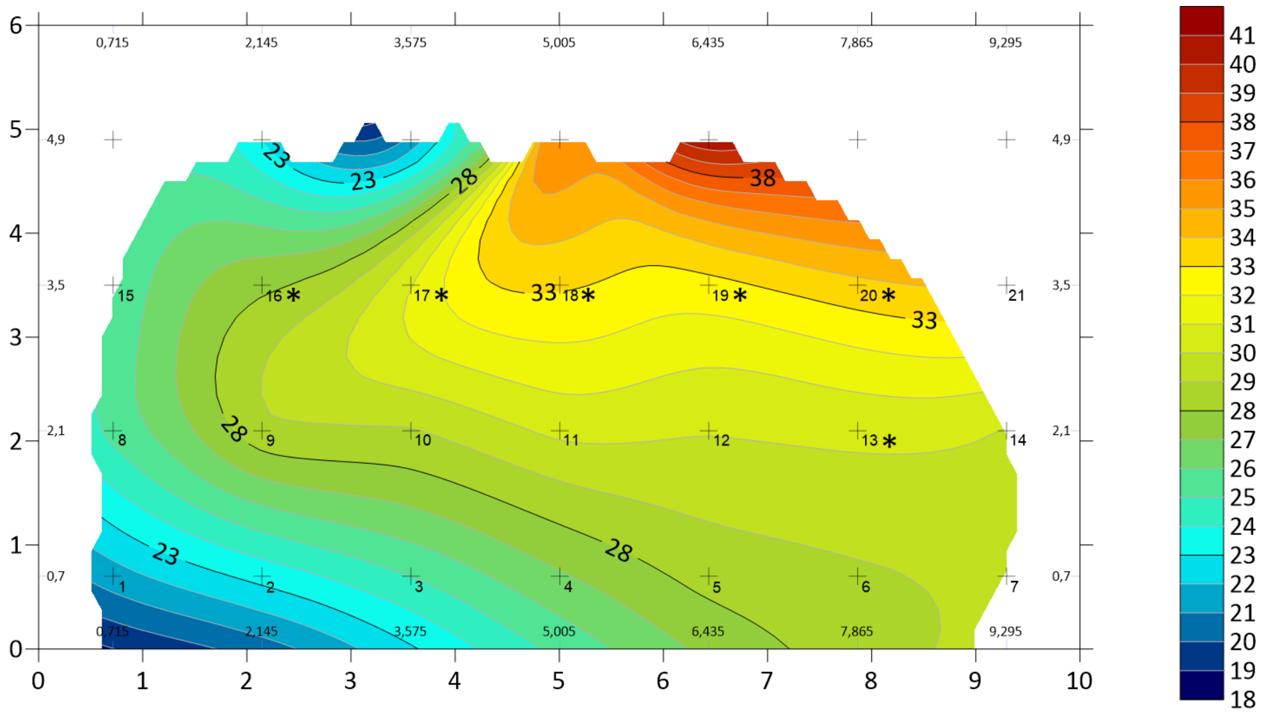
\+ measured locations # locations with closure of a tap-hole (Top of map indicates furnace end wall.)

Figure 3-3: Contour map of mean heat flux levels (W/m^2) on slag tap floor (locations removed where a tap-hole was closed).

3.4.1.2 WBGT

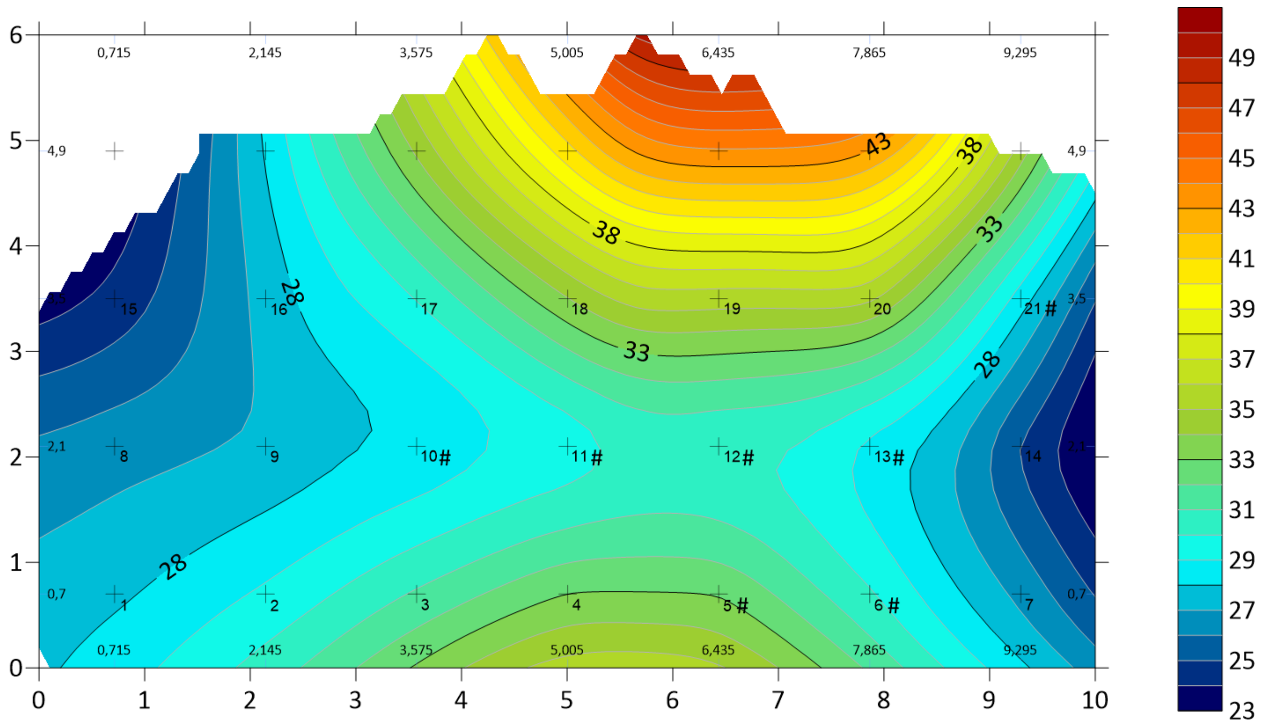
The distribution of $WBGT_i$ on the matte tap floor is indicated in Figure 3-4. The distribution on the slag tap floor is indicated when all measured locations are included (Figure 3-5) as well as when only those locations having all three tap-holes open (Figure 3-6).

$WBGT_i$ measured on the matte tap floor ranged from 21.04°C to 34.23°C, with the highest one-min value measured at location 21. On the slag tap floor, $WBGT_i$ ranged from 20.5°C to 38.2°C with the maximum being measured at location 18–19. Spearman's correlation revealed a statistically significant moderate to strong positive correlation between heat flux and WBGT on both the matte ($r_s(15) = 0.68$, $p = 0.006$) and slag tap floors ($r_s(19) = 0.67$, $p = 0.002$). Heat flux was not statistically significantly correlated with DB on either of the tap floors or with GT or WBT on the matte tap floor. A statistically significant correlation was however, found between heat flux and GT ($r_s(19) = 0.58$, $p = 0.009$) and between heat flux and WBT ($r_s(19) = 0.62$, $p = 0.005$) on the slag tap floor.



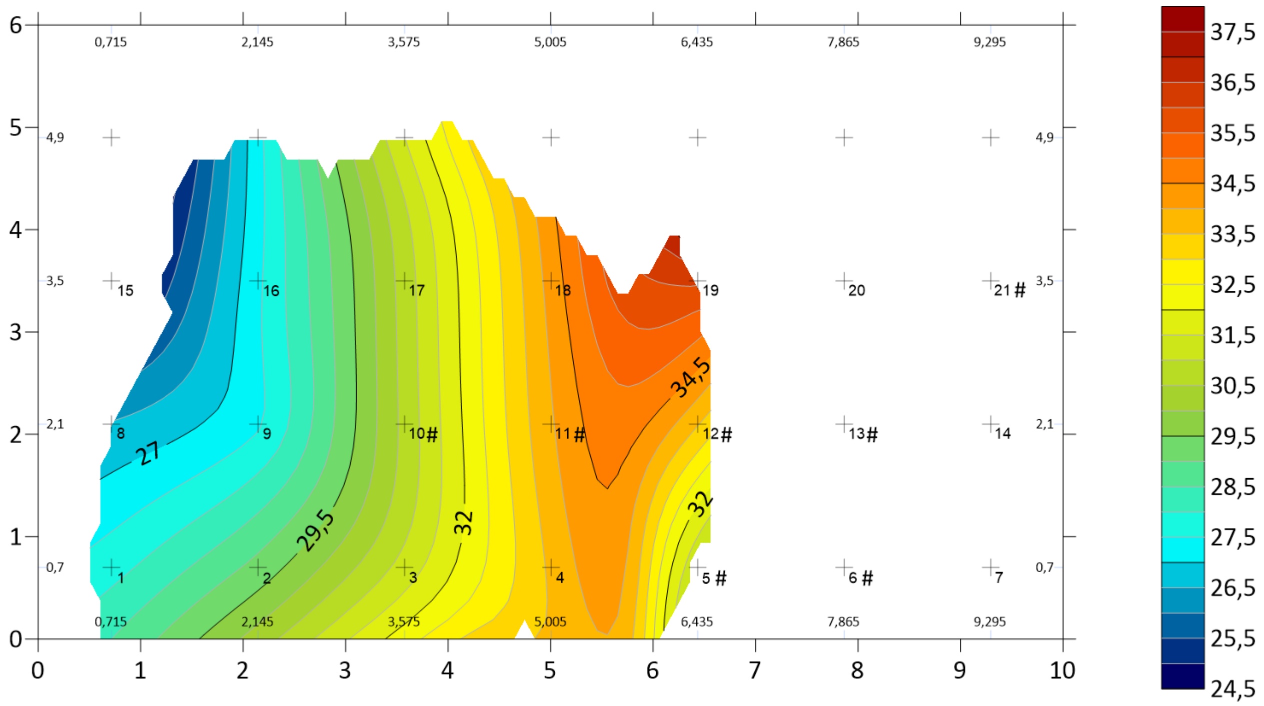
\+ measured locations   * locations within the grid that were not measured   (Top of map indicates furnace end wall.)

Figure 3-4: Contour map of mean $WBGT_i$ (°C) on matte tap floor.



\+ measured locations   # locations with closure of a tap-hole   (Top of map indicates furnace end wall.)

Figure 3-5: Contour map of mean $WBGT_i$ (°C) on slag tap floor (all locations).



+ measured locations   # locations with closure of a tap-hole   (Top of map indicates furnace end wall.)

Figure 3-6: Contour map of mean $WBGT_i$ (°C) on slag tap floor (locations removed where a tap-hole was closed).

3.4.2 Environmental conditions in other measured areas

Figure 3-7 compares the mean values for thermal variables in all the measured areas at the PGM smelter. The slag tap floor exhibited the highest mean DBT, GT and WBT of the four areas. Air velocity on and around the tap floors ranged from 0.15 to 2.03 m/s. The mean air velocity outdoors was 0.94 m/s ± 0.74 m/s.

3.4.3 Heat stress estimation

The TWA-$WBGT_{eff}$ levels for various hypothetical exposure scenarios based on the three locations frequented by furnace tappers, metabolic rate and clothing worn on the matte and slag tap floor are indicated in Table 3-3 and Table 3-4. The estimated CAVs are for the aluminised jacket and pant ensemble, assumed as 12 without a hood and 13 with a hood.

Table 3-3 and Table 3-4 indicate that the TWA-$WBGT_{eff}$ exceed the relevant limits posed by ISO 7243 in all scenarios except those in which 40 minutes are spent in the tapping cabin.

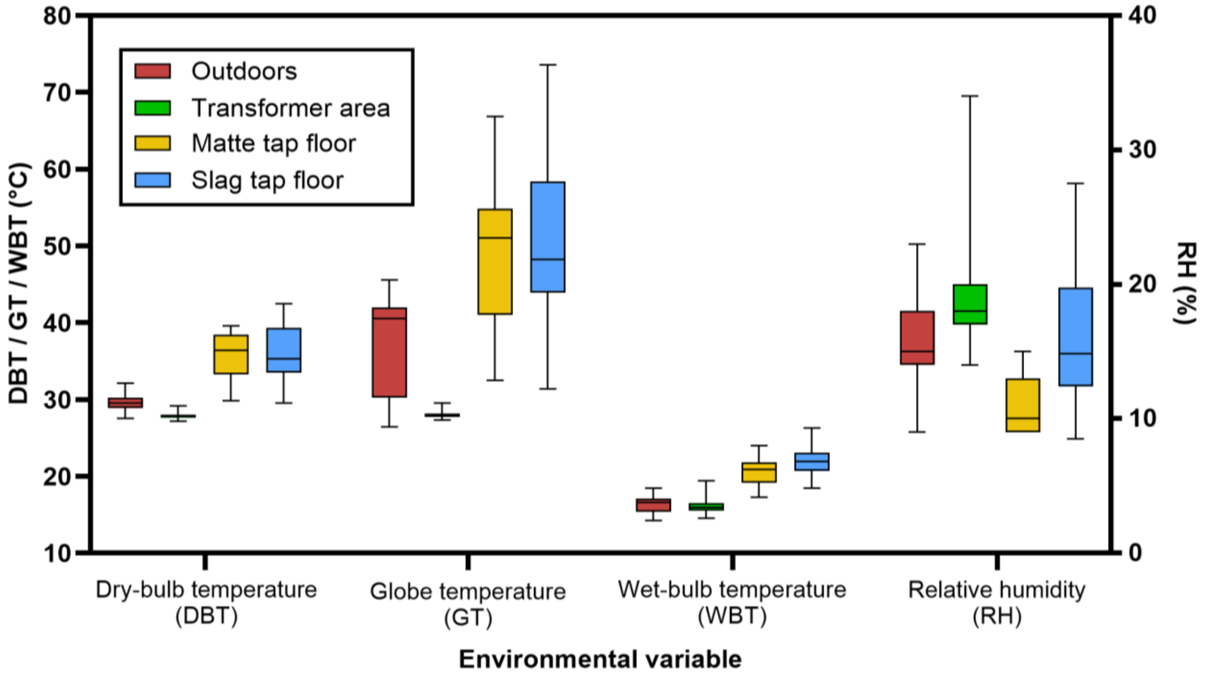


Figure 3-7: Environmental conditions across four measured areas at a PGM smelter.

Table 3-3: Time-weighted average effective WBGT (TWA-WBGT$_{eff}$) estimation on matte tap floor for a furnace tapper wearing an aluminised ensemble based on various exposure scenarios.

Scenario	**Exposure duration (min.)**			**Mean metabolic rate (W) calculated**	**TWA-WBGT$_{eff}$ (°C)**	**WBGT$_{eff}$ reference values (acclima-tised person) (°C)**
	Inside tapping cabin WBGT: 22.2 CAV: 0 Metabolic rate: Class 1 (180 W)	**Back of tap floor** WBGT: 26.2 CAV: 12 Metabolic rate: Class 2 (300 W)	**Front of tap floor** WBGT: 34.10 CAV: 13 (with hood) Metabolic rate: Class 2 (300 W)			
Rest focussed	40	10	10	130	29.0	32.3
	30	20	10	240	31.7	29
	20	30	10	260	34.4	28.7
Back focussed	10	40	10	280	37.0	28.3
	10	30	20	280	38.5	28.3
	10	20	30	280	40.0	28.3
Front focussed	20	10	30	260	37.3	28.7
	30	10	20	240	33.2	29
Even distribution	20	20	20	260	35.8	28.7

CAV – clothing adjustment value; W – watts; WBGT – wet-bulb globe temperature; °C – degrees Celsius; TWA-WBGT$_{eff}$ – time-weighted average effective wet-bulb globe temperature; WBGT$_{eff}$ – effective WBGT.
* Based on linear interpolation of reference values as specified in Table A.1 of ISO 7243 (2017).
The shaded area indicates a value above the reference value.

Table 3-4: Time-weighted average effective WBGT (TWA-$WBGT_{eff}$) on slag tap floor for a furnace tapper wearing an aluminised ensemble based on various exposure scenarios.

Scenario	Exposure duration (min.)			Mean metabolic rate (W)	TWA-$WBGT_{eff}$ (°C)	$WBGT_{eff}$ reference values* (acclimatised person) (°C)
	Inside tapping cabin WBGT: 25.7 CAV: 0 Metabolic rate: Class 1 (180 W)	**Back of tap floor** WBGT: 30.1 CAV: 12 Metabolic rate: Class 2 (300 W)	**Front of tap floor** WBGT: 30.4 CAV: 13 (with hood) Metabolic rate: Class 2 (300 W)			
Rest focussed	40	10	10	130	31.4	32.3
	30	20	10	240	34.1	29
	20	30	10	260	36.9	28.7
Back focussed	10	40	10	280	39.9	28.3
	10	30	20	280	39.8	28.3
	10	20	30	280	40.0	28.3
Front focussed	10	10	40	280	40.2	28.3
	20	10	30	260	37.3	28.7
	30	10	20	240	34.3	29
Even distri-bution	20	20	20	260	37.1	28.7

CAV – clothing adjustment value; W – watts; WBGT – wet-bulb globe temperature; °C – degrees Celsius; TWA-$WBGT_{eff}$ – time-weighted average effective wet-bulb globe temperature; $WBGT_{eff}$ – effective WBGT.

* Based on linear interpolation of reference values as specified in Table A.1 of ISO 7243 (2017).

The shaded area indicates a value above the reference value.

3.4.4 Heat flux

The maximum duration times as recommended by Heus and Denhartog (2017) for the measured heat flux levels on the matte and slag tap floors are indicated in Table 3-5. On the slag tap floor, all measured locations were included.

Table 3-5: Comparison of heat flux levels on matte and slag tap floors with recommended maximum durations for aluminised clothing.

Location	Matte tap floor		Slag tap floor	
	Mean measured heat flux (W/m^2)	Recommended maximum duration (s) at heat flux level*	**Mean measured heat flux (W/m^2)**	Recommended maximum duration (s) at heat flux level*
Inside tapping cabin	-60.8	No time limit (up to 4600 W/m^2)	-62.7	No time limit (up to 4600 W/m^2)
Back of tap floor	541		1060	
Front of grid (measured)	1021		2140	
Maximum on floor (extrapolated)	2091		3651	

W/m^2 – watts per square metre; s – seconds.
* maximum exposure durations specified by Heus & Denhartog for aluminised clothing (2017).

3.5 DISCUSSION

This study aimed to characterise the thermal conditions of the PGM furnace tap floor by measuring environmental variables such as heat flux, WBGT, DBT, WBT, GT and RH. The findings reveal a highly dynamic and spatially non-uniform thermal environment influenced by the proximity to radiant heat sources and operational activities.

The highest heat fluxes and WBGT values were recorded at locations closest to the front of the tap floor, near the furnace. For both variables, the maximal values observed on the slag tap floor exceeded those of the matte tap floor. This may be due to the liquidus temperatures of molten matte being lower than that of slag as is typical in the PGM smelting industry (Rivera Li Kao and Garbers-Craig 2024). In addition, the presence of three radiant heat sources (tap-holes) on the slag tap floor compared to only one source on the matte tap floor could have given rise to overall hotter conditions on the slag tap floor.

Hotter conditions were observed on the right-hand side of the matte tap floor (Figure 3-1 and Figure 3-4), since it was the right-hand (west) tap-hole and launder being used. On the slag floor, heat distribution was more symmetrical from left to right (Figure 3-2 and Figure 3-5), which correlates to three tap-holes of equivalent radiant intensity being tapped for most of the time. A hot spot is observed at the front and back of the slag tap floor, while the right and left sides exhibited cooler conditions.

Radiant heat, as governed by the inverse square law, demonstrates a pronounced sensitivity to distance (Boşdurmaz et al. 2019). For every metre the tapper moves closer to the source, the radiation will increase fourfold. This highlights the critical role of tapper positioning relative to heat sources in influencing the level of heat stress experienced.

The moderate to strong statistically significant positive correlation between WBGT and heat flux observed on the tap floors suggests that heat flux significantly contributes to the environmental heat stress experienced in this area. This finding aligns with the understanding that radiant heat is a major factor influencing WBGT, which is particularly important in environments where heat-generating processes dominate (e.g., smelting operations) (Patel et al. 2013). The correlation suggests that WBGT, which accounts for radiant, convective, and evaporative heat, may be a reliable proxy for estimating the radiant heat load, as indicated by heat flux measurements. However, heat flux provides a more direct measure of radiant heat, offering insights into localised thermal variability that WBGT alone may not fully capture.

Unexpectedly high DBT and WBT readings were recorded at Location 5 on the slag tap floor (Table 3-2) during a period when all three tap-holes were open, and the rightmost tap-hole was being drilled. This suggests that drilling activity may elevate localised temperatures beyond the levels typically observed during normal flow.

The mean values of DBT, WBT and GT of both the matte and slag tap floors at the PGM smelter exceed those reported by Westcott (2009) at the iron smelter. For instance, the mean GT on the PGM slag tap floor was 50°C in contrast to 32.5°C measured by Westcott while the mean

DBT on the PGM slag floor was 35.8°C in contrast to 24.8°C reported by Westcott (2009). In contrast to findings by Westcott (2009), who reported WBGT values that did not exceed those specified by ISO 7243, this study found WBGT values that exceeded these reference limits in most scenarios. This discrepancy is likely attributed to the inclusion of the CAV in this study, which was not applied by Westcott (2009). The results suggest that furnace tappers may be susceptible to developing heat stress if more than 20 minutes of any hour is spent on the tapping floor wearing aluminised clothing.

Interestingly, while WBGT values frequently exceeded recommended limits, heat flux measurements did not surpass the maximum durations set by Heus and Denhartog (2017). This apparent contradiction may reflect the differing nature of these metrics. WBGT integrates multiple environmental variables, including radiant heat (Budd 2008), while heat flux is a measure of heat transfer via conduction, convection and/or radiation depending on the measurement instrument used (Vega et al. 2015; Zribi et al. 2016). PPE, such as aluminised suits, is designed to mitigate incidental high heat flux levels but may not adequately prevent cumulative heat stress over a full shift.

Lastly, the woollen layer of the tappers' PPE is likely more vapour-permeable than aluminised suits, resulting in a lower heat burden. However, the simplified CAV adjustment used in this study may not fully capture the nuanced thermal properties of the layered clothing worn by tappers. Future research should aim to develop CAVs tailored to specific PPE ensembles and environments to improve the accuracy of heat stress assessments in high-radiation settings like smelters. Supporting this, Cortés-Vizcaíno and Bernard (2000) reported no significant difference in heat stress levels between flame-retardant clothing (specifically a Zirpro wool shirt and FR8 denim pants) and standard cotton work wear.

Additionally, the presence of reflective surfaces could have an influence on the radiant conditions on the tap floor. On the slag tap floor, a metal screen was installed at the back of the slag tap floor to protect workers not wearing tapping PPE, who pass from one side of the tap floor to the other. Thermal imaging showed the screen's temperature to be ~44°C. Radiant heat may be reflected to the tap floor by this screen.

Thermal conditions on the furnace tap floor are highly dynamic, with fluctuations influenced by operational activities such as drilling, tapping, and the number of active tap-holes. Spatial variability was also evident, with the highest WBGT and heat flux values observed near active tap-holes.

3.6 LIMITATIONS

This study has limitations that should be considered for generalisation and interpretation. Although conditions on the day were warm for the time of year (April) data collection did not take place during the hottest summer months, i.e. January, due to urgent request by the smelter (client) and the availability of the research team. Consequently, the environmental conditions recorded may not represent the worst-case scenario for heat stress. On the matte tap floor, six of the locations within the grid were not measured and the values for these locations were extrapolated instead. This extrapolation likely influenced the comparison between the two tap floors, as the excluded areas are expected to exhibit higher environmental heat stress levels. On the slag tap floor seven locations, predominantly from the middle row, were measured while only two of the three tap-holes were open, impacting the consistency of data across locations. CAVs specific to the types of clothing worn by furnace tappers in this study are not available. The CAV selected for the aluminised ensemble was that of vapour-barrier coveralls, which may not accurately reflect the actual clothing configuration. This discrepancy may lead to an overestimation of heat stress when using a CAV of 12 for workers wearing aluminised clothing. Finally, worker metabolic rates were estimated based on observed activities rather than measured directly, introducing potential errors in the metabolic rate values.

3.7 CONCLUSION

This study characterised the thermal environment of the furnace tap floors using environmental monitoring equipment. The tap floor exhibits non-uniform thermal environments, with conditions varying considerably across different locations. Heat distribution on the matte tap floor was more concentrated around the active launder while the slag tap floor displayed a more symmetrical thermal environment. WBGT and heat flux were found were found to have a moderate to strong, positive, and statistically significant correlation, suggesting that further studies may investigate its potential use as a proxy for traditional heat stress measurements. Elevated thermal conditions on the tap floors pose a significant risk for heat stress among furnace tappers. This risk is influenced by a worker's proximity to the tap-hole and the duration of exposure, emphasising the importance of spatial variability in understanding thermal hazards. The findings of this study can assist in developing tailored protective solutions and workplace interventions to mitigate heat stress.

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CHAPTER 4 CONCLUDING CHAPTER

This chapter is divided into four sections, namely conclusions, recommendations for control measures, limitations, and future studies. These sections are discussed with reference to the aim, objectives and research question posed in Chapter 1. Recommendations that could be implemented by the smelter (employer) to control heat stress in furnace tappers (employees) are made, the limitations of the study are addressed, and finally, potential future studies are suggested.

4.1 Conclusions

This study aimed to characterise the thermal environment of the furnace tap floor at a platinum group metals (PGMs) smelter. This was achieved by using environmental monitoring instruments placed at specific locations within a defined grid on the tap floors to quantify various thermal variables. Conditions on the matte and slag tap floors were recorded using a QUESTemp° 36 (TSI® Incorporated, Shoreview, Minnesota, USA) heat stress monitor and a Hot Cube thermal comfort measurement system (Hukseflux Thermal Sensors, Delft, Netherlands). Conditions were also recorded outdoors and in an open area in the transformer area (Table 3-1, Chapter 3).

The first objective of this study was to quantify environmental factors (heat flux, dry-bulb temperature [DBT], wet-bulb temperature [WBT], globe temperature [GT], relative humidity [RH] wet-bulb globe temperature [WBGT] and air velocity) on the matte and slag tap floors. The slag tap floor exhibited the following mean levels of the measured thermal variables: 35.6 ± 3.6°C (DBT), 22.1 ± 1.9°C (WBT), 50 ± 10.4°C (GT), 16.2 ± 5.5% (RH) and 29 ± 3.7°C (indoor wet-bulb globe temperature [$WBGT_i$]). The matte tap floor exhibited the following levels of these variables: 35.8 ± 3.1°C (DBT), 20.8 ± 1.8°C (WBT), 48.5 ± 9.2°C (GT), 11.1 ± 2.3% (RH) and 27.8 ± 3.2°C ($WBGT_i$) (Table 3-2 of Chapter 3). Mean heat flux levels were 974 ± 537 W/m² on the slag floor and 554 ± 458 W/m² on the matte floor. A statistically significant moderate to strong positive correlation between heat flux and WBGT was found using Spearman's correlation coefficient, $r_s(15) = 0.68$, $p = 0.006$ for the matte floor and $r_s(19) = 0.67$, $p = 0.002$ for the slag floor. This aligns with the understanding that radiant heat is a major influencer of WBGT in industrial environments containing radiant heat sources (Patel et al. 2013). Mean DBT, WBT and GT on both tap floors exceeded those measured by Westcott (2009), suggesting that the PGM tap floor environment may be hotter than the iron tap floor environment.

The second objective of this study was to assess and compare the spatial distribution of the measured environmental factors within and across the matte and slag tap floors. As illustrated in

Figure 3-2 and Figure 3-5 (Chapter 3), heat distribution (in terms of heat flux and $WBGT_i$) was comparatively symmetrical on the slag tap floor with a large hotspot at the front of the floor, smaller hot spot at the back of the floor, and colder regions on the sides. This is likely due to the location of the furnace and tap-holes and the presence of a metal screen at the back of the tap floor. Heat was more concentrated within a diagonal channel running from the centre front to the back left of the slag tap floor, which may be a result of air movement. Heat distribution on the matte tap floor was concentrated on the right-hand side of the floor (see Figure 3-1 and Figure 3-4 Chapter 3) since it was the right tap-hole being used during data collection.

The third objective of this study was to evaluate the environmental heat stress and radiant heat flux levels on the tap floors in relation to reference values. Contrary to the findings by Westcott (2009), the time weighted average effective WBGT values on the PGM tap floors exceeded the limits set by ISO 7243 (ISO 2017) in most scenarios, which may be attributed to the inclusion of a clothing adjustment value (CAV) in this study. Assuming a CAV of 12 for the aluminised clothing worn by furnace tappers, heat stress limits would be exceeded if more than 20 minutes were spent on the tap floors (Table 3-3 and Table 3-4, Chapter 3). These findings suggest that during tapping-intensive shifts, workers may be exposed to excessive heat stress and at risk of heat-related illnesses. In contrast, heat flux levels did not exceed the limits for aluminised clothing (Table 3-5, Chapter 3) suggested by Heus and Denhartog (2017), stipulating no maximum duration of exposure up to 4600 W/m^2. The three objectives of this study were all achieved.

In Chapter 1 the research question was posed: What are the environmental conditions on the tap floors of an electric furnace at a PGM smelter? The results indicated that the matte and slag tap floors present distinct and non-uniform thermal environments, with elevated thermal conditions that pose a risk of heat stress to furnace tappers depending on location. The quantification of heat flux, a variable not typically considered in heat stress studies, offered an improved understanding of the thermal environment by quantifying the contribution of radiant heat, enhancing spatial mapping and revealing correlations with heat stress metrics.

4.2 Recommendations

- Recommendation 1: Climatic conditions can significantly influence the level of heat stress experienced by furnace tappers. It is recommended that the study be repeated in January, the hottest month of the year for the region, to capture the extreme heat conditions. Additionally, measurements should be taken over multiple days to account for any variability, considering all combinations of tap holes being open or closed. Finally, using instruments with shorter recording intervals would improve the accuracy and resolution of temperature and heat stress data.

- Recommendation 2: The level of heat stress experienced by furnace tappers on the tap floor is likely highly dependent on the duration spent in different areas of the tap floor. Therefore, the use of real-time heat stress monitoring devices for furnace tappers that provide immediate data on physiological variables and raise alarm when heat strain risk is high, are recommended. Commercially available devices of this kind include the Armor Heat Monitor (which measures heart rate and Physiological strain index) (Evalan, Amsterdam, Netherlands) and the Bodytrak® Personal Safety Monitor System (which measures core body temperature and heart rate at the inner ear) (Bodytrak®, Miami, Florida, USA).
- Recommendation 3: Giahi et al. (2016) reported a lowering of 20°C in the mean radiant temperature and 3.9°C in WBGT following the installation of a heat absorbing system to a steel blast furnace. The system utilises cooled water from a cooling tower that is circulated through tubing integrated into the furnace's surface, to cool down the body of the furnace. It is recommended that a study be conducted to assess the feasibility of this solution in the PGM tap floor environment.
- Recommendation 4: Aluminised fabric possesses low vapour permeability (Bitgen and Kutlu 2020), a property of clothing that limits the tolerance to heat stress (Goldman 2002). Personal cooling garments (PCGs) incorporating convective cooling methods have previously been used at the PGM smelter, however, the practical application of these devices posed challenges that prevented their use. Tetzlaff et al. (2024) reported that the greatest thermoregulatory benefit was achieved from conductive and hybrid PCGs and it is therefore recommended that PCGs of this type are implemented.
- Recommendation 5: Although quantitative data are vital to inform the design of personal protective garments by manufacturers, the value of qualitative information should not be overlooked. Furnace tappers can be involved in the development and evaluation of new PPE designs. Their first-hand experience and insights into challenges like heat accumulation, mobility restrictions, and task-specific needs are invaluable for creating PPE that is both effective and practical in the smelting environment. This collaboration can be achieved using focus groups or structured interviews with workers and controlled on-site testing of prototypes.
- Recommendation 6: It was observed that the metal screen at the back of the slag tap floor reached moderately high temperatures and could be a reflector of radiant heat. When furnace tappers crossed the tap floor, they passed near this screen. Therefore, it is recommended that the screen is either replaced with a screen made of materials that have higher absorbance and lower reflectivity or that a high-absorbance coating or paint is applied to the screen, which may minimise the reflection of radiant heat to the tap floor.

- Recommendation 7: An air conditioning system installed in the slag tapping cabin was set to 17°C. However, the temperature inside the tapping cabin was 25.7°C. It was noted that the metal cabin was not well insulated and had many outlets and gaps to the outside. Therefore, it is recommended to line the walls and roof of the cabin with high-performance thermal insulation materials and seal any unnecessary gaps to reduce heat ingress from the external environment. The installation of an air curtain may also be considered.

4.3 Limitations

- The study was conducted in April rather than during the peak summer months due to urgent request by the smelter (client) and the availability of the research team. The results are limited by the potential underestimation of maximum heat stress levels that workers could experience during summer, which may affect the generalisability and applicability of the findings to year-round operations.
- Data collected on a single day fails to account for inter-day variability in thermal conditions and tapping practices. This limitation restricts the representativeness of the data and may not fully capture the range of heat stress conditions encountered across different days, especially under atypical or extreme operational scenarios.
- The measurement grid was not positioned at the very front of the tap floor, representative of the position of oxygen lancing, due to risk of damage to instrumentation. As a result, the recorded levels of thermal variables may not fully represent the more intense heat exposure experienced in these high-risk positions.
- Six locations within the measurement grid on the matte tap floor were not assessed, with most of these being in the front row nearest to the furnace. This omission limits the study's ability to characterise high-risk zones accurately. As a result, the recorded data may underestimate the actual thermal conditions in these critical zones. In addition, seven locations on the slag tap floor were measured under conditions where one of the tap-holes was closed. While this scenario reflects more typical, everyday conditions on the slag tap floor, it does not capture the thermal extremes that could occur during worst-case scenarios, such as when all tap-holes are open or during particularly intense tapping operations.
- On the matte tap floor, measurment time was limited to approximately 25 minutes due to the short duration of a tap. As a result, the instrument was left at each location for only one minute, allowing minimal time for the sensors to adjust to the new conditions. A lag period was observed in the Hot Cube sensors, necessitating a two-minute adjustment to the heat flux data. This adjustment introduces potential inaccuracies, particularly regarding the positional precision of measurements.

- The metabolic rate of workers was not directly measured during the study but was instead estimated based on observed activity levels. This estimation method may not fully capture the variability in workers' actual metabolic rates, as it relies on assumptions regarding their level of exertion.
- Worker exposure was represented by WBGT measurements calculated at three fixed locations. In practice, workers move across the tap floor, encountering varying heat levels and environmental conditions.
- The effects of clothing can be complex, and the CAV is a simple adjustment and first approximation for accounting for personal heat stress. In addition, the effects of radiant heat on the CAV are unknown and this is of high importance in a radiant heat environment such as the furnace tap floor (ISO 2017). CAVs for the specific clothing worn by the furnace tappers – namely the Zirpro woollen suits and aluminised jacket and pant ensembles – are not provided by ISO 7243 (ISO 2017). As a result, the CAVs for these specialised garments were assumed to be equivalent to those for vapour-barrier clothing. This assumption may not accurately reflect the thermal properties and insulation characteristics of the Zirpro woollen suits and aluminised ensembles, potentially leading to inaccuracies in the heat stress evaluation. Unlike a one-piece garment, the aluminised ensemble consists of a jacket or coat combined with pants, likely providing lower insulation than a one-piece vapour-barrier coverall.

4.4 Future studies

- This study, conducted in autumn, revealed heat stress levels that may pose health risks to furnace tappers. A future study may be repeated in the summer months to investigate the effect of ambient temperatures on the thermal conditions of the tap floor.
- The tap floor area presented a dynamic thermal environment where furnace tappers are exposed to a wide range of thermal conditions and follow varying movement patterns. Future research can explore the use of wearable heat stress sensors and perform quantitative time-motion analyses to provide more detailed assessments of tappers’ exposure profiles. The reliability and accuracy of these sensors in comparison to traditional methods and their feasibility as a control measure to mitigate heat stress in smelting environments could also be investigated.
- Environmental conditions were found to vary depending on the number of open tap-holes and the stage of smelting. Future studies should investigate how the number of operational tap-holes affects thermal conditions and heat stress during activities such as launder scraping and maintenance tasks.

- In parallel with heat stress monitoring, it is recommended to assess the heat strain experienced by furnace tappers. Wearable sensors may also be tested as a supplementary tool for real-time monitoring of physiological parameters related to heat stress.
- Parsons (2006) suggested that swatches of clothing material be placed around the wet bulb - and globe thermometers for measuring WBGT when vapour impermeable clothing is worn. This would allow the effect of clothing to be considered at the measurement stage and eliminate the need for clothing adjustments to the WBGT limits. A validation study of this nature using aluminised material as worn by furnace tappers is recommended.
- Heat flux correlated significantly with WBGT on the matte and slag tap floors. Future studies may investigate the feasibility of using heat flux measurements as a proxy for heat stress, traditionally evaluated using the WBGT index.
- Furnace tappers experience first-hand the difficulties associated with the hot tap floor environment and the wear of specialised protective clothing. A qualitative study utilising surveys or structured interviews with furnace tappers is recommended to explore their perceptions, challenges, and coping strategies related to heat stress. This approach can capture the subjective experiences of workers and identify potential gaps in current control measures.
- A CAV for the aluminised suit ensembles worn by furnace tappers is not provided by ISO 7243 (ISO 2017). A study is suggested to estimate the thermal insulation and vapour resistance of aluminised suits according to ISO standard 9920 (ISO 2007) to determine a CAV for these suits and compare this adjustment to the measured heat strain experienced by tappers.

4.5 References

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ANNEXURE A: ETHICS APPROVAL LETTER

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South Africa 2520

Tel: 086 016 9698
Web: http://www.nwu.ac.za/

North-West University Health Research Ethics Committee (NWU-HREC)

Tel: 018 299-1206
Email: Ethics-HRECApply@nwu.ac.za (for human studies)

9 April 2024

ETHICS APPROVAL LETTER OF STUDY

Based on approval by the North-West University Health Research Ethics Committee (NWU-HREC) on 09/04/2024, the NWU-HREC hereby approves your study as indicated below. This implies that the NWU-HREC grants its permission that, provided the general conditions specified below are met and pending any other authorisation that may be necessary, the study may be initiated, using the ethics number below.

Study title: Thermal characterisation of the tap floor of a submerged arc furnace at a South African platinum-group metals smelter
Principal Investigator/Study Supervisor/Researcher: Mr CJ van der Merwe
Student: DA Stoppel - 25141147

Ethics number:

N	W	U	-	0	0	1	9	3	-	2	3	-	A	1
Institution				Study Number						Year			Status	

Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Application Type: Single study
Commencement date: 09/04/2024
Expiry date: 30/04/2025

Risk: **Medium**

Approval of the study is provided for a year, after which continuation of the study is dependent on receipt and review of a six-monthly monitoring report and the concomitant issuing of a letter of continuation. Monitoring reports are due at the end of October and April annually until completion of the study.

General conditions:

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, the following general terms and conditions will apply:

- *The principal investigator/study supervisor/researcher must report in the prescribed format to the NWU-HREC:*
  - *six-monthly on the monitoring of the study, whereby a letter of continuation will be provided annually, and upon completion of the study; and*
  - *without any delay in case of any adverse event or incident (or any matter that interrupts sound ethical principles) during the course of the study.*
- *The approval applies strictly to the proposal as stipulated in the application form. Should any amendments to the proposal be deemed necessary during the course of the study, the principal investigator/study supervisor/researcher must apply for approval of these amendments at the NWU-HREC, prior to implementation. Should there be any deviations from the study proposal without the necessary approval of such amendments, the ethics approval is immediately and automatically forfeited.*
- *Annually a number of studies may be randomly selected for active monitoring.*
- *The date of approval indicates the first date that the study may be started.*

9.1.5.4.2 Ethics Approval Letter of Study 1

- *In the interest of ethical responsibility, the NWU-HREC reserves the right to:*
  - *request access to any information or data at any time during the course or after completion of the study;*
  - *to ask further questions, seek additional information, require further modification or monitor the conduct of your research or the informed consent process;*
  - *withdraw or postpone approval if:*
    - *any unethical principles or practices of the study are revealed or suspected;*
    - *it becomes apparent that any relevant information was withheld from the NWU-HREC or that information has been false or misrepresented;*
    - *submission of the six-monthly monitoring report, the required amendments, or reporting of adverse events or incidents was not done in a timely manner and accurately; and/or*
    - *new institutional rules, national legislation or international conventions deem it necessary.*
- *NWU-HREC can be contacted for further information via Ethics-HRECApply@nwu.ac.za or 018 299 1206*

The NWU-HREC would like to remain at your service and wishes you well with your study. Please do not hesitate to contact the NWU-HREC for any further enquiries or requests for assistance.

Yours sincerely,

Chairperson NWU-HREC

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20 August 2019
File Reference: 9.1.5.4.2

ANNEXURE B: LANGUAGE EDITING

In addition to formal language editing services, this dissertation benefitted from the use of OpenAI's ChatGPT to assist with language refinement.

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27 November 2024

LANGUAGE EDITING STATEMENT

I, Jannetje Levina De Kock hereby declare that the thesis

Thermal characterisation of the furnace tap floor environment
of a platinum group metals smelter

by

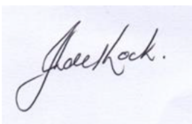
Danay Stoppel

Student number: 25141147

for submission to the OHHRI, NWU.

- has been edited for language correctness and spelling.
- has been edited for consistency (repetition, long sentences, logical flow)

No changes have been made to the document’s substance and structure (nature of academic content and argument in the discipline, chapter and section structure and headings, order and balance of content, referencing style and quality).



J L DE KOCK

ANNEXURE C: SIMILARITY REPORT

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