



Comparison of airborne particulate exposure in two platinum refining process areas.

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Preface

For the aim of this study the article format was used. The *Annals of Occupational Hygiene* journal was chosen as the potential publication and for that reason the whole dissertation is written according to the guidelines of this journal. The journal requires that references in the text should be inserted in Harvard style, and in the Vancouver style of abbreviation and punctuation in the list of references, with the list in alphabetical order by name of the first author.

This study was planned and executed by a team of researchers. The contribution of each researcher is depicted in Table 1.

Table 1: Research team and contributions

NAME	CONTRIBUTION
Mrs. Z. Selenati-Dreyer	<ol style="list-style-type: none">1. Planned and executed sampling.2. Researched topic, analyzed and interpreted results, compiled and completed dissertation.
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Mr. J.L. du Plessis	<ol style="list-style-type: none">1. Assistant-supervisor2. Assisted with the approval of the protocol, interpretation of the results and reviewing of the dissertation.

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 Zoé Selenati-Dreyer's M.Sc (Occupational Hygiene) dissertation.

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SUMMARY

The aims and objectives: The aims and objectives of this study were to characterize and compare the airborne particulate matter in the tankhouse and crusher areas of a base metal refinery sampled with two separate methods, in terms of mass concentration, nickel content, and particle size distribution. Methods: Area sampling was conducted in the two areas. Two methods were applied to collect particulate samples. The first is a multi-stage virtual impactor, the Respicon, which was used to determine the three critical particle fractions (inhalable, thoracic and respirable). The NIOSH 7300 method determined the particle concentration and nickel percentage present in each fraction. Using formulas provided by the manufacturers two additional particle-size fractions (extra-thoracic and trachea-bronchial) could be calculated. The second was based on the standard NIOSH 0500 method, which determined particle size distribution depicted as cumulative percentages. The samples were analyzed using laser scattering instrumentation. Results: In the tankhouse the highest level of exposure was to particles bigger than 10 μm , with the highest nickel percentage also falling into this range. However, high nickel percentages were present in all three cut-off sizes (4 μm , 10 μm and > 10 μm). The particle concentration for the crusher area was the highest for particulates bigger than 10 μm , with the highest nickel percentage present in this fraction. After comparing the tankhouse and crusher areas, it is clear that the particle concentration is much higher in the crusher area according to all sampling methods used. The nickel content present in the analysis of these areas is of great concern. Conclusion: With the knowledge obtained through this research one hopes to establish a basis for particle size sampling in the platinum mining industry. This may lead to the development of health based OEL's and reflect a more accurate evaluation of workers particulate exposure. This information will give a greater understanding of health risks workers are exposed to.

Keywords: airborne particulate matter; particle size; nickel; particle fractions; platinum mining.

OPSOMMING

Doelstellings: Die doelstellings vir hierdie studie was om die partikel konsentrasie, nikkel persentasie, partikel grootte distribusie en partikel fraksies van die lugdraende partikel massa in die tankhouse area van 'n basis metaal raffinadery en "crusher" area van 'n smelter te evalueer en vergelyk. **Metode:** Area monsterneming was uitgevoer in die twee areas. Twee metodes was gebruik om die partikel monsters in te samel. Die eerste metode word 'n meervoudige fase impaktor, die Respicon gebruik. Deur hierdie metode word die drie kritiese partikel fraksies (inhaalbare, torakale en respireerbare) bepaal. Die NIOSH 7300 metode het die partikel konsentrasie en nikkel persentasie wat teenwoordig was in elke fase bepaal. Daar is gebruik gemaak van 'n formule wat deur die vervaardigers verskaf is om twee additionele fraksies (ekstra-torakaal en tragea-brongiaal) te bereken. Die tweede metode is gebaseer op die standaard NIOSH 0500 metode. Die monsters was geanaliseer deur 'n laser verspreidings instrument wat partikel grootte distribusie as 'n kumulatiewe persentasie voorstel. **Resultate:** In die tankhouse was die hoogste vlakke van blootstelling aan partikels groter as 10 µm, met die grootste nikkel persentasie wat ook onder hierdie fraksie val. Daar moet wel gelet word dat hoë nikkel persentasies in al drie afsny-groottes (4 µm, 10µm en > 10 µm) teenwoordig was. Die partikel konsentrasies vir die "crusher" area was die hoogste vir partikels groter as 10 µm, met die hoogste nikkel persentasie ook in hierdie fraksie. As die twee areas met mekaar vergelyk word is dit duidelik dat die partikel konsentrasies veel hoër in die "crusher" area is as die tankhouse area, volgens al die metodes gebruik. Die nikkel inhoud teenwoordig in beide areas wek kommer. **Gevolgtrekking:** Met die kennis verkry deur hierdie navorsing word daar gehoop om 'n basis vir partikel-grootte monsterneming in die platinum myn industrie vas te stel. Dit mag lei tot die ontwikkeling van gesondheidsgebaseerde BBD's (Beroepsblootstellings Drempel) en 'n meer akkurate evaluasie van die werkers se partikel blootstelling. Daar word gehoop dat die inligting in hierdie studie die leser 'n beter begrip sal gee vir die gesondheidsrisikos waaraan werkers blootgestel word.

Sleutelwoorde: lugdraende partikel stof; partikel grootte; nikkel; partikel fraksies; platinum myn industrie.

ABBREVIATIONS AND ACRONYMS

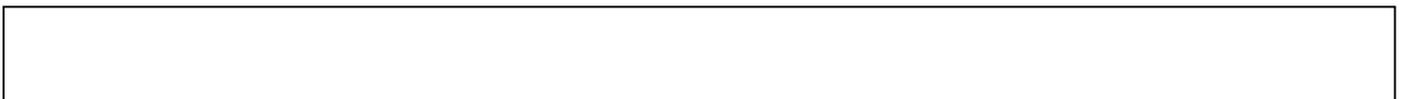
ACGIH	American Conference of Governmental Industrial Hygienists
ASTMC	American Society for Testing and Materials
ATSDR	Agency for Toxic Substances and Disease Registry
BSI	British Standards Institute
CSIR	Council for Scientific and Industrial Research
DMR	Department of Minerals and Resources
EAP	United States Environmental Protection Agency
GER	Gas Exchange Region
HAR	Head Airway Region
HSE	Health and Safety Executive
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
IOM	Institute of Occupational Medicine
ISO	International Organization for Standardization
ISO/CEN	International Organization for Standardization/European Standardization Committee
MCE	Mixed Cellulose Ester
MHSA	Mine Health and Safety Act
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
OELs	Occupational Exposure Limits
OSHA	Occupational Safety and Health Administration
PSS	Particle Size Selective
SIMRAC	Safety in Mines Research Advisory Committee
TBR	Tracheobronchial Region

CHAPTER 1: INTRODUCTION

INTRODUCTION

Airborne particulate matter is ubiquitous in the atmosphere. Particulate pollutants consist of finely divided solids or liquids such as smoke, dust, fumes, mist, smog and sprays (Hinds, 1999). Particulate matter has many characteristics such as size and composition that depend on the source and history of the particle (Kim & Hu, 2006). Particulate matter emission and exposure is produced through transportation, blasting, processing, handling and various other operations making respiratory exposure to airborne particulates a main concern and health hazard in many mining industries (Petavratzi *et al.*, 2005).

The respiratory tract is the most common means of entry for airborne particulates into the human body because of respiration. The close air-blood contact in the lungs makes it easy for chemical particulates to be absorbed and distributed systematically (Andrew *et al.*, 2003; Klaassen & Watkins, 2003; Vincent, 1999). This physiological knowledge was the basis of the start of total dust gravimetric sampling in the breathing zone of exposed workers as early as the 1900's and was used to determine potential hazards (Vincent, 1999). A few years' later industries started separating non-respirable from respirable dust as total dust samples overestimated the hazards of exposure (Vincent, 1999). Researchers also discovered that the behaviour, deposition and fate of particulates after entry into the human respiratory system, and the response that they elicit, depends on the nature and size of the particles (Kim & Hu, 2006; Klaassen & Watkins, 2003; Hofmann *et al.*, 2003; Sandström *et al.*, 2005). Thus the concentrations of airborne particles for occupational hygiene purposes may be measured in terms of the different size fractions, namely: inhalable ($< 100\mu\text{m}$), thoracic ($< 10\mu\text{m}$) and respirable ($< 4\mu\text{m}$) fractions (Vincent *et al.*, 2001; Vincent, 1999; Phalen, 1999). The inhalable particulates are the dust mass that can enter the body through breathing and is hazardous when deposited anywhere within the respiratory tract. Thoracic particulate mass is deposited beyond the larynx and in the gas exchange regions. The alveolar region is penetrated by the respirable mass fraction of total dust (Belle & Stanton, 2007; Klaassen & Watkins, 2003; Ramachandran, 1996; Vincent, 1999). Vincent (1999) states that deposition probabilities in each region can be used to relate the anatomical locations of various diseases to the sizes of particles that tend to cause these diseases. It is clear that the



total sampled mass is being replaced by particle size-specific mass, as the latter provides a better index for determining the actual health hazard of the aerosol. The characteristics of airborne particulates, *i.e.* particle size and concentrations are important factors for hygienists in characterizing the possible health effects of airborne dust at workplaces (Höhr *et al.*, 2002; Wilson *et al.*, 2002). Thus particulate sizing plays an important role in the control of health hazards of workers exposed to airborne particulates.

In the mining industry different mining methods are used, materials with different properties are produced, different operational-processing activities exist and atmospheric conditions and locations differ. This means that different sizes of particulates are produced, with different chemical properties and differs in the impact it would have on the exposed workers health. In the South African mining sector all operations need to comply with the Department of Minerals and Resources' (DMR) requirements and standards of particulate exposure. However, particulate size is not taken in to consideration when standards and requirements are set. This leads to inaccurate characterization of health risks associated with particulate exposure. Taking the different processes in consideration and investigating the characteristics of the airborne particulates a more accurate risk assessment could be made. It may also lead to developing process specific standards. If the particle size distribution can be determined for airborne particulates, the respiratory deposition may be anticipated and a more accurate health risk of workers may be established. Sivulka *et al.* (2005) support this by stating that future respiratory-based Occupational Exposure Limits (OELs) will be formulated concentrating solely on the particle fraction that is relevant to the health risks at hand.

In this study nickel is being applied to investigate the characterization of airborne particulate exposure in the platinum processing industry. The most common health effect of nickel and nickel compounds in humans is an allergic reaction that mostly results in skin dermatitis (ATSDR, 2005). Nickel and nickel compound exposures are also believed to result in lung fibrosis, asthma and more seriously, cancer of the respiratory tract. The carcinogenicity of insoluble nickel has been extensively researched in human and animal studies over the past few decades and exposures have been linked to malignant tumours in the respiratory tract (ATSDR, 2005; Costa &

Klein, 1999; Kasprzak *et al.*, 2003; Klaassen & Watkins, 2003; Öller, 2002; Salnikow & Kasprzak, 2005). Assessment of the carcinogenicity of soluble nickel compounds has proven to be a very difficult task. Some researchers claim that soluble nickel compounds may be carcinogenic but overall research has yet to prove this theory. In animal studies done where soluble nickel compounds were solely administered, no malignant tumours were formed. It is believed that the combination of insoluble and soluble nickel elevates the carcinogenicity of soluble nickel compounds (Öller, 2002; Denkhaus, 2002; Haber *et al.*, 2000). More research needs to be done before the carcinogenic potential of soluble nickel compounds can be discarded.

Although health effects of nickel and nickel compounds have been a key research topic over the years, most researchers have concentrated on total or just inhalable fraction sampling. The MSHA threshold for soluble nickel is 0.1 mg/m³ while for insoluble nickel it is set at 1.0 mg/m³. In both cases total dust is measured and particle size is not taken into consideration. There seems to be a lack of knowledge and research on the precise particulate size of nickel particles workers are exposed to, with a small number of studies investigating the potential of particulate size selective sampling in the nickel mining industry.

AIMS AND OBJECTIVES

The aims of this study are to characterize and compare the airborne particulate matter in the tankhouse and crusher areas of a base metal refinery sampled with two separate methods, in terms of mass concentration, nickel content, and particle size distribution.

HYPOTHESIS

There is a significant difference in the airborne particulate matter found in the tankhouse and crusher areas in terms of the mass concentration, nickel content and particle size distribution.

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CHAPTER 2: LITERATURE REVIEW

In the literature review important key points will be discussed. A closer look will be taken at dust and aerosols, the origin and criterion of particle size selective (PSS) sampling and the value of particle size selective based sampling. The deposition of airborne particulates in the respiratory tract and airborne nickel particulates will be investigated.

1. DUST AND AEROSOLS

In the mining industry dust is one of the biggest occupational hazards and is generated by a wide range of processes (Petavratzi *et al.*, 2005). In processing operations dust is emitted when ore is broken by impact, abrasion, crushing and grinding. Dust can also be generated by dispersing settled dust in the atmosphere through activities such as loading, transferring and dumping (Burdett *et al.*, 2000; Trade Union Congress, 2001). A summary of some of the sources of dust is summarized in Table 1.1.

Dust is a result of mechanical disintegration of matter and can be defined as a collection of solid particles (Petavratzi *et al.*, 2005). In general dust is dispersed in a gaseous medium, is able to remain suspended in the gaseous medium for an amount of time and has a high surface area to volume ratio (BSI, 1994). Another characteristic of dust is that it can be re-dispersed into the atmosphere after it has settled on a surface (OSHA, 2009). Dust emission is the process where dust is lifted from the surface to become suspended in the atmosphere. Energy is needed to overcome gravitational and cohesive forces that bind the particles to the surface. The means of distributing particles in the atmosphere are influenced by both the weight of particles and the inter-particle forces and the drag, lift and movement causes by the flow of air on the particles (Liu *et al.*, 1999). Movement by workers or machinery can re-circulate previously generated dust (OSHA, 2009). Dispersion of particles is also greatly affected by the weather conditions. Wet weather will reduce dust emission whilst dry wind will spread dust over a larger geographical area (Arup Enviromental, 1995).

A wide range of particle size and shapes is produced during a dust generating process. The geometric diameters of airborne particles may vary between

0.001 μm and 100 μm . Particles that are too large to remain airborne settle, while others remain in the air indefinitely (OSHA, 2009). For particles to remain airborne the aerodynamic drag force must be larger than the sum of the particle weight and the inter-particle forces (Liu, *et al.*, 1999). Molecular forces influence the small particles that will behave as a gas in the ambient air, while larger particles are affected by gravitational and inertial forces (SIMRAC, 2003).

The behaviour of dust is a complex topic with a wide range of factors playing a role in the way dust reacts. It must be understood that not all dust produced has the same health effects. Factors listed below are considered critical properties from a health and safety point of view (SIMRAC, 2003).

i) Dust composition (Chemical/mineralogical)

Dust may affect the human body in different ways and may cause harmful effects through different physiological routes, for example through skin or eye contact and inhalation, depending on individual physical and chemical properties (HSE, 1997).

ii) Dust concentration (On a mass basis/on quantity basis)

Dust concentration can be defined as the mass of particulate matter in a unit of volume air. The unit used to describe this characteristic is mg/m^3 .

iii) Particle size and shape

Many dust properties depend on the particle size of dust, thus making it a very important parameter (Petavratzi *et al.*, 2005). Particle size is often described by the diameter of the particle. According to Allen (1997), the most commonly used diameter is the aerodynamic diameter, which is defined as the diameter of a hypothetical sphere of density 1 g/cm^3 , having the same terminal velocity in calm air as the particle in question, regardless of its geometric size, shape and true density.

iv) Exposure time (Excessive/ long-term exposure)

Excessive exposure to airborne particulates increases the potential health risks. The respiratory system has adapted to withstand the continuous

presence of airborne particles, but with long term, excessive exposure these clearance and defense mechanisms fail (McClellan, 2000).

2. PARTICLE SIZE SELECTIVE SAMPLING

The major aim of particle size-selective sampling in occupational hygiene is to develop an accurate index of particulate matter health risks by incorporating the characteristics of particle size that can greatly influence the regional deposition within the respiratory tract (Lippmann, 1999).

2.1 History of particle size selective sampling

Over the past decades particle size-specific sampling of workers in an occupational setting has begun to supplement or replace total mass sampling, as it was clearly proven through research that total mass concentration ignored the fact that the deposition site of a particle within the respiratory tract may at times control the extent of the hazard (Lippmann, 1999). In 1983, International Organization for Standardization (ISO) was the first to establish multiple particle size-selective criteria which consisted of inhalable, thoracic and respirable fractions. ISO also developed a separate criteria for respirable dust for occupational and community exposures. ISOs' criteria were based on the idea of dividing particles into these three forms that correspond with the site of deposition in the respiratory tract. For example, the thoracic fraction refers to particles reaching the tracheobronchial region as well as the gas exchange region for deposition. This criterion makes it possible to divide particles into three categories (inhalable, thoracic and/or respirable fractions) according to their aerodynamic properties and if composition of the particles is known and relatively constant, the gravimetric analysis may be used for particulate size-selective risk assessment (Hinds & Zhu, 2008; Maynard & Kuempel, 2005). Particle size-selective sampling equipment specifications and procedures required to assess occupational situations where workers are exposed to potential hazardous aerosols were defined in 1982 by the American Conference of Governmental Industrial Hygienists (ACGIH) Air Sampling Procedure Committee.

In the 1985 report the committee established a basis for threshold limit values (TLV's) dividing individual compounds according to particle size in terms of the physiological or biochemical responses or pulmonary diseases associated with each (Phalen, 1985). Since the establishment of the basic fundamentals of size-selective sampling by the ACGIH, minor modifications have been made by including new scientific knowledge and making changes applicable to different international standards. The increase in the median cut point for respirable particulate matter sampler from 3.5 μm to 4 μm is probably the most important modification of the ACGIH definitions. The change was made based on the International Organization for Standardization/European Standardization Committee (ISO/CEN) protocol (ACGIH, 2009).

In 1987 the US EPA (United States Environmental Protection Agency) changed their approach and replaced total suspended particulate matter with thoracic particulate matter as measured in terms of PM₁₀ on the basis that particulate matter exposure responsible for primary health effects was limited to particles depositing in the tracheobronchial and gas exchange airways. Thus the PM₁₀ sampling criterion represented a conservative approximation of the ambient particles that could penetrate through the head airways to the thorax (Miller *et al.*, 1979). As time passed and particulate matter exposure was reviewed it became evident that adverse health effects were associated more with fine particles, as measured by PM_{2.5}, than the larger coarse particles expressed by PM₁₀ (US EPA, 2005; McClellan, 2002). Based on above findings PM_{2.5} was added to the existing PM₁₀ sampling criteria. The US EPA decided to require a 50% cut-off at 2.5 μm based on the fact that these particles are derived from different sources and have different chemical compositions and not on regional respiratory deposition (Wolff, 1996). In other words, 50% of the particles would penetrate through the impactor and the other 50% would be collected on the filter. It would be certain that 50% of the particles are 2.5 μm (Trakumas & Salter, 2009).

In the past few years there has been an increased emphasis on the health impact of particles in the sub-micrometer and nanometer size range. Epidemiological studies (Dockery *et al.*, 1993; Schwartz & Morris, 1995; Seaton *et al.*, 1995; Wichmann & Peters, 2000; Pope *et al.*, 2002) have shown an increased morbidity

and mortality with exposure to particulate matter smaller than 10 μm and 2.5 μm (Brown *et al.*, 2002). More recently nano-structured particles have attracted much interest in the research field of occupational health, and research into the potential occupational health risks associated with inhaled nano-particles has just begun (Maynard & Kuempel, 2005). Also, the dosimetry of nano-particles in the human lung is not well developed (Brown *et al.*, 2002). It is clear that exposure to nano-particulate matter needs to be addressed, but before it can be included in occupational sampling a few critical research questions need to be answered. At present no defined exposure risks are available for nanomaterials and limited research has been done addressing the adverse health effects of nanomaterial exposure in the workplace. There also seems to be limited quantitative data available needed for a full scale risk assessment. According to Maynard and Keumpe (2005) sufficient information is available to start preliminary assessments.

2.2 Particle size criterion

The particle size distribution is especially important in occupational health because it determines the regional deposition of inhaled aerosols in the different parts of the human respiratory tract (European Committee for Standardization and British Standard Institute, 1993; Hlavay *et al.*, 1998; Pui, 1996). Three fractions of particulate mass: inhalable ($< 100\mu\text{m}$), thoracic ($< 10\mu\text{m}$) and respirable ($< 4\mu\text{m}$) are widely being used in sampling based on health-related particle size of airborne particulates (Vincent *et al.*, 2001; Vincent, 1999; Phalen, 1999). This criterion was adopted by the ACGIH in the 1987 annual TLV/booklet and is still in use today (ACGIH, 2009).

2.2.1 Inhalable fraction

This fraction indicates all matter that can be deposited anywhere in the respiratory tract. The cut-off point for these particles is 100 μm . It is accepted that these large particles will be deposited in the head airways region (Lippmann, 1999; Phalen, 1999).

2.2.2 Thoracic fraction

The thoracic fraction indicates the particles which are deposited in the lung airways with a cut-off point of 10 µm (Lippmann, 1999; Phalen, 1999).

2.2.3 Respirable fraction

The respirable fraction indicates the particles that are deposited in the gas exchange region, with a cut-off point of 4 µm. For sampling purposes a cut-off point of 2.5 µm is used. It was introduced in 1997 when the EPA revised the National Ambient Air Quality Standards for particulate matter as it was clear that higher protection was needed against particulate matter health effects (EPA, 1997). This decision was made based on research findings that 2.5 µm was the minimum value between fine and coarse particles (John, 1993). A 2.5 µm cut separates the fine particles from the coarse particles each with its own physical and chemical properties and origin. Further, it is understood that fine particles are more likely to be associated with adverse health effects (Zhang *et al.*, 1998).

2.3 Value of particle size based sampling

Applying size-selective sampling in the occupational hygiene field, where it is known, exposure limits are generally more chemical specific can be beneficial for determining what amount of chemical substance will be available for deposition within the different respiratory tract regions. It must be kept in mind that a sound understanding of particle deposition within the respiratory tract (as it varies according to the aerodynamic particle size) and accurate collection and analysis of size segregated samples by conducting specialized procedures is crucial. Findings in industrial situations have shown drawbacks, such as the fact that particles do not always have homogenous chemical compositions and thus the toxicant will not always distribute uniformly, as a percentage of mass, over the range of particles emitted in a particular working environment (Lippmann, 1999).

Due to the fact that individual particles have a wide range of chemical and physical properties and that the significance of particle size-specific sampling has been highlighted, it is imperative that particle size-selective OELs need to be

developed. Sampling procedures have already been identified where one or more particle size range is expected to contain a certain compound (Sivulka *et al.*, 2007). It should now be apparent that with development of accurate PSS-OELs additional information will be needed, such as particle size associated with the substance of interest, its effects after deposition, and its rate of dissolution in the different sites in the respiratory tract (Lippmann, 1999).

3. DEPOSITION OF AIRBORNE PARTICULATES IN THE RESPIRATORY TRACT

Deposition and transport processes of particulate matter in the respiratory tract are highly dependent on the size of the particle (Nazaroff, 2004). Hinds & Zhu (2008) also highlight the important role particle size plays in characterizing the rate and location of deposition, uptake, transport to different organs and clearance of deposited particles.

Over the past years different respiratory deposition area models were introduced by a number of institutions. The ACGIH reviewed these models and developed their own terminology, which in their opinion, distinguished better between regions, was anatomical correct and unambiguous. Table 1.2 is an overview of these models (adopted by Lippmann, 1999). It should also be noted that, at present, the regional deposition in the human respiratory tract is still not fully understood and is influenced by a variety of factors, thus using the predictive models is only an approximation (Lippmann, 1999; Maynard & Kuempel, 2005).

3.1 Respiratory regions and deposit mechanisms

The ACGIG model divides the respiratory system into three parts, based upon the anatomical qualities and clearance mechanisms within each region, as well as particle deposition in each region according to the particle size. Using this identification tool as a guideline when studying inhalable particulates can be of great use to occupational hygienists (Phalen, 1999). The benefit of utilizing this model is that one can predict the deposition of inhaled particles within the respiratory tract. The three region model can be applied to a total deposition

curve by performing some mathematical calculations and adapting the measurement of particles to correspond accordingly. Thus, the total deposition curve is broken up into three components, one for each region. It is possible, when the deposition probabilities of each region are known, to link anatomical locations of various diseases to the size of particle that tend to cause these diseases (Phalen, 1999; Lippmann, 1999). Utilizing this model in sampling criteria in practice may be a valuable tool in the occupational health and hygiene sector.

The head airways region (HAR) is classified as region 1. It begins at the anterior un-ciliated nares and includes the ciliated nasal passages, olfactory epithelium, nasal pharynx, nasopharynx, pharynx and larynx (Lippmann, 1999). During mouth breathing larger particles primarily deposit in this region due to the fact of inertial properties that cause impaction in the nasal passages or entrapment by nasal hairs. Particles are also removed from inhaled air by electrostatic forces and sedimentation (Lippmann, 1999; Lieutier-Colas, 2001). Very small particles sometime settle in this region due to contact with the airway walls by diffusion (Phalen, 1999). During mouth breathing, some inhaled particles are deposited in the oral cavity primarily by impaction. These particles are rapidly removed to the esophagus by swallowing (Lippmann, 1999).

Region 2 is the tracheobronchial region (TBR). The region begins at the trachea and includes the ciliated bronchial airways which divide into smaller bronchioles which divide further into terminal bronchioles. The topic of deposition in this region is very complex due to the anatomical and physical properties and differences that occur within this region. The diameter decreases as the bronchial airway divides, but because of the increasing number of tubes, the cross section for flow increases due to the increased number of tubes and rate and the air velocity decreases towards the end of the bronchial branches. Particles that are too large to pass through the airway bends in the large airways are deposited by inertial impaction and sedimentation. In smaller airways where the velocities are low, particles deposit, if small enough, by Brownian diffusion (Lippmann, 1999; Swietlicki, 2006).

The gas exchange region or GER is region 3 and refers to the functional gas exchange sites of the lung. It includes the respiratory bronchioles, alveolar ducts, alveolar sacs and alveoli. For particles to reach and deposit in this region they need to penetrate the two more proximal regions on inspiration to come into contact with deep lung surfaces by mechanisms such as settling, diffusion or interception (Phalen, 1999; Maynard & Kuempel, 2005). Due to the gas exchange there is between tidal and residual air, a portion of each breath remains, which gives the particles in the un-exhaled air a longer time to deposit. Insoluble particles are deposited in this region by sedimentation and diffusion and with the epithelium being unciliated, these particles are removed at a very slow rate (Lippmann, 1999). Other insoluble particles may move through the alveolar wall and enter the lymphatic system keeping their original shape and physical properties (Swietlicki, 2006). According to Vincent (1995), there is a portion of insoluble particles that may become isolated either by immotile macrophages or in fixed tissue and cannot be cleared and result in cumulative lung health risks.

It must be understood that there are major factors that play a role in the deposition of particles in each region such as particle aerodynamic size, the subjects' airways dimensions and breathing characteristics (flow rate, breathing frequency, tidal volume to name a few) (Lippmann, 1999; McClellan, 2002).

3.2 Respiratory defenses (clearance)

Inhaled particulate matter is cleared from the respiratory tract by a number of mechanisms. The HAR region is cleared of particles directly by the mucociliary transport system. The most anterior part of the nasal passages does not contain cilia and particles are removed by the flow of mucus from the back of the nose to the front. Particles are generally more rapidly removed by sneezing, wiping or nose blowing (McClellan, 2002). Insoluble particles that are deposited in the oral or nasal passages may be moved to the gastrointestinal tract and cleared from the respiratory tract by swallowing.

In the TBR region the mucociliary escalator, which moves particles to the pharynx via the mucus layer on top of the ciliated epithelium is the main clearance

mechanism for insoluble particles. Soluble particles may dissolve in this region, diffuse to surrounding cells and be transported to the blood (McClellan, 2002). Clearance mechanisms in the TBR may not be uniform across the region; the bronchial surfaces are not homogenous areas as unciliated cells occur at the bifurcation regions and may be responsible for retarded clearance (Maynard & Kuempel, 2005; Kuempel *et al.*, 2001a, b).

The particle clearance mechanisms of the HAR region are still not clearly understood, there are a few mechanisms that are believed to be responsible for disposal of particulate matter. Dissolution of soluble particles directly into the blood circulation, phagocytosis of insoluble particles by macrophages ingestion and translocation to the ciliated airways, transfer of particles to the lymphatic channels, vessels and lymph nodes are believed to be responsible for any clearance (ICRP, 1994; NCRP, 1997).

It is imperative to note that the 3 region model has drawbacks that need to be addressed when applied to any study or processing of data. Some of the problems that Phalen (1999) identified are that the pattern in which particles deposit within a certain region is not included in the model. It must not be assumed that particle deposition is uniform in a certain region; it may lead to inaccurate risk assessment. The example of the bifurcation sites of the terminal bronchioles are given, where it is highlighted that there are structural and anatomical differences within a region. There is also not a definite separation between the terminal bronchioles and the alveolar ducts and sacs, and the model does not include the unique structures of the respiratory bronchioles that have both properties of the bronchial airways and gas exchange area (Maynard & Kuempel, 2005).

4. AIRBORNE NICKEL PARTICULATES

4.1 Overview

Nickel is a natural, ubiquitous element that makes out an important part of the earth's crust. Pure nickel is silvery-white in colour and is characterized by being a hard but pliable and malleable metal. It is also ferromagnetic, relatively resistant

to corrosion and is a fair conductor of heat and electricity. It is these characteristics that makes nickel a sought-after metal. Nickel is mostly combined with iron, copper, chromium and zinc to form valuable alloys widely used in the jewellery and manufacturing industries and manufacturing of coins. Electroplating is another major use of nickel. A large quantity of nickel is used to produce stainless steel (ATSDR, 2005; Sivulka, 2005; Profumo *et al.*, 2003).

Due to the fact that nickel is such a common element found in water, soil and air, humans may be exposed to nickel through different routes such as ingestion, inhalation and dermal exposures (Sivulka, 2005). According to the Agency for Toxic Substances and Disease Registry (ATSDR) (2005), the general population is exposed to insignificant amounts of nickel and it is unlikely to ingest nickel through water or food. Higher levels of airborne nickel may be found in heavily industrious areas. Nickel is primarily a risk and health hazard in an occupational setting whether it be mining, alloy production or manufacturing industries (Denkhaus & Sivulka, 2002). The most common route of occupational nickel and nickel compound exposure is inhalation, making it the main priority of standard-setting bodies, with the most emphasis on respiratory effects (Sivulka *et al.*, 2007).

Nickel combines with many other elements forming different nickel compounds or species each with its own physiochemical properties and biological effects (Öller, 2002). These properties have a great influence in the result of nickel and nickel compound exposure. Common species of nickel are nickel sulfide, nickel carbonyl and nickel salts which include nickel oxide, nickel sulfate, nickel chloride and nickel acetate. Common applications for these compounds include manufacturing of batteries, plated coatings, certain pigments, ceramic glaze and as industrial and laboratory catalysts. Nickel sub-sulfide is used in refining certain ores and smelting operations (ATSDR, 2005; Gad, 2005; IARC, 1997; Sivulka *et al.*, 2007).

4.2 Toxicology

It is important to remember that every specie of nickel has its own toxicity that is determined by its physical and chemical properties such as particle size and solubility in water and biological fluids (Gad, 2005). Small particles will penetrate the respiratory tract and deposit in the bronchiolar region and alveoli through sedimentation while larger particles mainly deposit in the nasopharyngeal area through inertial impaction (ATSDR, 2005). Nickel chloride and nickel sulfate are highly soluble in water while nickel sub-sulfide is not completely water soluble. However, when submerged in biological fluid this changes and nickel sub-sulfide becomes more soluble due to proteins and other cellular components being present (Gad, 2005). Nickel oxide on the other hand is not water soluble at all. Nickel and its inorganic compounds are not well absorbed through the skin or the gastrointestinal tract. Inhaled airborne soluble nickel particulates are rapidly absorbed and distributed while insoluble particles are retained in the respiratory tract much longer. Nickel may act at the point of contact or systematically. Once soluble nickel is absorbed it is transported by plasma to the rest of the body but mainly to the kidneys where it leaves the body through the urinary tract (ATSDR, 2005; Gad, 2005).

4.3 Health effects of airborne nickel and nickel compounds

As mentioned above, the difference in toxicity of different species of nickel is evident and has a direct impact on the health risk it signifies. Over the past few decades the exposure to nickel and the subsequent impact as a health hazard has been investigated in a number of studies i.e., workplace exposure studies, laboratory studies and animal studies.

The most common health effect of nickel is contact dermatitis – an allergic reaction of the skin. After direct and prolonged contact a person may become sensitized to nickel. Once a person is sensitized, further contact may produce a delayed-type hypersensitivity reaction which results in inflammation of the affected area. Blisters and a red itchy rash accompanied by a burning sensation

are common symptoms of allergic dermatitis. It may take a few hours to fade away although in some cases it takes days to heal (ATSDR, 2005; Kimber *et al.*, 2002).

Nickel compounds may also lead to an array of adverse health effect through chronic exposure such as lung fibrosis, cardiovascular and kidney diseases (Kasprzak *et al.*, 2003). Nickels carcinogenic properties are the most serious of all, being an important factor in the risk assessment of nickel in an occupational setting. Metallic nickel is classified by the International Agency for Research on Cance (IARC) (1997) as possibly carcinogenic to humans (Group 2B) whereas nickel compounds are seen as carcinogenic to humans specifically for lung, nasal cavity and para-nasal sinuses (Group 1). In the past it was believed that only insoluble nickel had carcinogenic effects on humans, but new research has proven that some soluble compounds may also have carcinogenic effects on the human body and more so in the presence of insoluble nickel compounds (Haber *et al.*, 2000; Sivulka, *et al.*, 2007). In the review article of Haber *et al.*, (2000) the difficulty of determining the exact carcinogenicity of soluble nickel is highlighted. In the majority of epidemiological studies investigated no research could prove what ratio of insoluble nickel and soluble nickel was the most carcinogenic. Exposure to other chemicals such as sulfuric acid mist or arsenic that may play a role in the carcinogenicity of soluble nickel is not always taken in consideration. However, it is well documented in animal studies where soluble nickel was solely inhaled, that there is no carcinogenic risk (Öller, 2002; Sivulka *et al.*, 2007). Much controversy around the carcinogenicity of soluble nickel is clearly being seen in resent research evidence. Sivulka *et al.*, (2007) review two studies where controversy around soluble nickel is eminent. The first, research done by Grimsrud *et al.* (2002) on Norwegian refinery workers found exposure to soluble nickel to be a significant factor in the cancer risk of workers. The second study, by Sorahan and Williams (2005) once again found no definite respiratory carcinogenic risk of exposure to soluble nickel. This research was done on Welsh refinery workers with at least 5 years of employment working in the highest risk of soluble nickel exposure area. Due to the fact that research has not yet been able to fully prove the potential soluble nickel has as a carcinogenic agent it is difficult to discard the carcinogenicity of soluble nickel totally.

Chronic exposure to insoluble nickel, especially nickel sulfide and nickel subsulfide has been linked to an increased risk of lung and nasal cancer (ATSDR, 2005). Animal inhalation studies have shown that the most potent form for causing respiratory cancer is nickel subsulfide (ATSDR, 2005; Denkhaus *et al.*, 2002; Öller *et al.*, 1997). The ATSDR (2005) reports on research where rats had a significant increase in the development of benign and malignant lung tumours after nickel subsulfide was administered through inhalation. Intratracheal administration also resulted in malignant lung tumours. The EPA also classifies nickel refinery dust and nickel subsulfides as carcinogenic to humans. Extensive research has been done during the past decades on the carcinogenicity and health effects of insoluble nickel exposure (IARC, 1990; Haber *et al.*, 2000; Öller *et al.*, 1997; Sunderman *et al.*, 1959; Ottolenghi *et al.*, 1975; Saknyn & Blokhin, 1978) just to name a few. It is obvious to come to the conclusion that insoluble nickel has adverse health effects after chronic exposure and that the necessary precautions should be taken when exposure is inevitable.

5. A SUMMARY OF RELEVANT AIRBORNE NICKEL EXPOSURE STUDIES

Although health effects of nickel and nickel compounds have been a key research topic over the years, most researchers have concentrated on total or just inhalable fraction sampling. There seems to be a lack of knowledge and research on the precise particulate size of nickel particles workers are exposed to, with a small number of studies investigating the potential of particulate size selective sampling in the nickel mining industry.

Kiilunen *et al.* (1996) investigated the exposure to soluble nickel in electrolytic nickel refining. The study included area and personal air sampling measurements as well as biological monitoring by means of blood and urinary nickel analysis. Although the study gave insight into workers nickel exposure; it did not distinguish between the different fractions of nickel exposure that correspond with the respiratory deposition model widely being used. It was found that the median

count diameter of the particles was 12 μm ; most particles were $> 5 \mu\text{m}$ in diameter. The three tank houses had mean exposure averages to soluble nickel of 0.112 mg/m^3 , 0.324 mg/m^3 and 0.484 mg/m^3 respectively.

In a more recent review study by Sivulka *et al.* (2007) the shift to particle size selective sampling for the different nickel species is emphasized. The purpose of the article was to review the basis for setting inhalable occupational exposure standards. It is noted that the most particle size-selective distribution data have been collected using either the Institute of Occupational Medicine (IOM) Personal Inhalable Dust Spectrometer or a modified Andersen cascade impactor used as a stationary area sampler. Six operational processes were identified in the nickel mining industry. For the purpose of this study, only findings in the feed preparation and aqueous operations will be discussed. A modified version of the summary of findings can be seen in Tables 1.3 and 1.4. In Table 1.3 it is clear that exposure to nickel in the aqueous operations (electrolysis and electrorefining) consists mainly of soluble nickel compounds, making out the largest percentage of total inhalable nickel dust exposure, ranging from 74 to 90%. The largest percentage of the inhalable nickel dust exposure in the feed preparation operations (matte crushing and processing; matte room; granulation; grinding) consisted mainly out of sulfidic nickel compounds ranging from 68 to 81%. The findings of these studies highlight the differences one finds between different operations within one industry. It is not accurate to assume nickel exposure is uniform across all sectors of the nickel mining and processing industry. When studying the findings depicted in Table 1.4, it is evident that the particle size data available for the different nickel operations are limited.

Table 1.1. Dust sources in mineral sites (adapted by Petavratzi *et al.*, (2005) from Arup Environmental, 1995 and Mohamed *et al.*, 1996)

Operation and equipment	Emission Mechanism	Relative Potential contribution to total site dust levels	Primary source	Secondary Source
Drilling and blasting	Air flush from drilling and from force of blast	Small	+	-
Loading and dumping	Dropping material from heights	Moderate	-	+
Draglines	Dropping material from heights	Large	-	+
Crushing and preparation	Impact, abrasion and dropping from heights	Large	+	-
Conveyors	Dropping from heights	Small	0	-
Haulage roads	Raised by tyres, exhaust and cooling fans	Large	0	+
Storage piles	Wind blow, high wind speeds	Small	0	-

(+) Signifies a major source, (-) signifies a minor source, (0) signifies a negligible source.

Table 1.2. Respiratory regions as defined in particle deposition models (adopted by Lippmann, 1999)

ACGIH Region	Anatomical Structure Included	ISO Region	1966 ICRP Task Group Region	1994 ICRP Task Group Region	1997 NCRP Task Group Region
Head Airways (HAR)	Nose Mouth Nasopharynx Oropharynx Laryngopharynx	Extrathoracic (E)	Nasopharynx (NP)	Anterior Nasal Passages (ET ₁) All other Extrathoracic (ET ₂)	Naso-oropharyngolaryngeal (NOPL)
Tracheobronchial (TBR)	Trachea Bronchi Bronchioles (to terminal bronchioles)	Tracheobronchial (B)	Tracheobronchial (TB)	Trachea and Large Bronchi (BB) Bronchioles (bb)	Tracheobronchial (TB)
Gas Exchange (GER)	Respiratory bronchioles Alveolar ducts Alveolar sacs Alveoli	Alveolar (A)	Pulmonary (P)	Alveolar Interstitial (AI)	Pulmonary (P)

Table 1.3. Summary of the nickel exposures in the milling and aqueous operations (mg/m³) (Modified from Sivulka *et al.*, 2007)

Industry operation (number of personal samples taken)	Average inhalable nickel dust (standard deviation)	Inhalable nickel: species % of total inhalable nickel over species mean exposure			
		Metallic	Soluble	Oxidic	Sulfidic
Nickel species *					
1. Feed preparation (Tsai <i>et al.</i>, 1995; Werner <i>et al.</i>, 1999., Vincent <i>et al.</i>, 2001)					
Canada (Company A)					
Matte crushing (6)	0.47 (0.390)	14/0.070	4/0.019	9/0.042	73/0.343
Matte processing (12)	1.19 (1.704)	12/0.143	3/0.036	17/0.202	68/0.810
Canada (Company B)					
Feed preparation (6)	0.151 (0.175)	9/0.014	11/0.017	8/0.012	72/0.109
Matte room (3)	0.169(0.093)	9/0.015	11/0.019	8/0.014	72/0.122
Granulation (2)	0.175 (0.035)	9/0.016	11/0.019	8/0.014	72/0.126
Norway					
Grinding **(12)	0.478 (Not given)	7/0.034	7/0.035	4/0.018	81/0.391
2. Aqueous operations (Werner <i>et al.</i>, 1999; Thomassen <i>et al.</i>, 1999)					
Norway					

Electrolysis** (13)	0.059 (Not given)	< 1/negligible	90/0.053	8/0.005	2/0.001
Russia					
Electrorefining ** (14)	0.34 (0.26)	3/0.010	74/0.252	12/0.041	13/0.044

* Different samplers were used to collect data for species analysis: Canada – modified Andersen cascade impactor; Norway – IOM sampler; Russia - 25 mm sampler.

** Percentages do not precisely add to 100% due to rounding.

Table 1.4. Particle size data for nickel aerosols in the feeding preparation and aqueous operations (Modified from Sivulka *et al.*, 2007)

Industry operation	Inhalable mass as percent of total nickel aerosol	Thoracic and respirable mass as a percent of inhalable nickel aerosol	
		Thoracic	Respirable
1. Feed preparation (Vincent, 1996; Vincent <i>et al.</i>, 2000)			
Canada (Company A)	67	61	27
Canada (Company B)	74	65	27
Norway	63	33	10
2. Aqueous operations (Vincent, 1996; Thomassen <i>et al.</i>, 1999)			
Norway	58	22	9
Russia	Not given	“Very little”	“Non-existent”

* Particle size data for companies in Canada was collected using a modified Andersen cascade impactor, while a Personal Inhalable Dust Spectrometer was used in Norwegian and Russian companies.

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CHAPTER 3:

ARTICLE

Title: Comparison of airborne particulate exposure in two platinum refining process areas.

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ABSTRACT

The aims and objectives: The aims and objectives of this study were to characterize and compare the airborne particulate matter in the tankhouse and crusher areas of a base metal refinery sampled with two separate methods, in terms of mass concentration, nickel content and particle size distribution. Methods: Area sampling was conducted in the two areas. Two methods were applied to collect particulate samples. The first is a multi-stage virtual impactor, the Respicon, which was used to determine the three critical particle fractions (inhalable, thoracic and respirable). The (National Institute for Occupational Safety and Health) NIOSH 7300 method determined the particle concentration and nickel percentage present in each fraction. Using formulas provided by the manufacturers, two additional particle-size fractions (extra-thoracic and trachea-bronchial) could be calculated. The second was based on the standard NIOSH 0500 method, which determined particle size distribution depicted as cumulative percentages. The samples were analyzed using laser scattering instrumentation. Results: In the tankhouse the highest level of exposure was to particles bigger than 10 μm , with the highest nickel percentage also falling into this range. However, high nickel percentages were present in all three cut-off sizes (4 μm , 10 μm and > 10 μm). The particle concentration for the crusher area was the highest for particulates bigger than 10 μm , with the highest nickel percentage present in this fraction. After comparing the tankhouse and crusher areas, it is clear that the particle concentration is much higher in the crusher area according to all sampling methods used. The nickel content present in the analysis of these areas is of great concern. Conclusion: With the knowledge obtained through this research one hopes to establish a basis for particle size sampling in the platinum mining industry. This may lead to the development of health based (Occupational Exposure Limits) OELs and reflect a more accurate evaluation of workers particulate exposure. This information will give a greater understanding of health risks workers are exposed to.

Keywords: airborne particulate matter; particle size; nickel; particle fractions; platinum mining.

INTRODUCTION

Airborne particulate matter is one of the most common constituents of the atmosphere (Hinds, 1999). Exposure to airborne particulates is a serious health matter for occupational hygienists throughout the mining sector. Airborne particulates are produced by different mechanical and operational processes in the mining industry such as transportation, handling, blasting and various other operations (Petavratzi, *et al.*, 2005). Thus, whenever materials are handled or broken down particulates are produced and are mainly associated with affecting the respiratory system of exposed workers (Trade Union Congress, 2001).

The most common means of entry of airborne particulates into the human body is through the respiratory tract. Particle size has shown to influence the deposition, behaviour, fate of particulates and biological response it elicits after entering the respiratory tract (Kim & Hu, 2006; Klaassen & Watkins, 2003; Vincent, 1999). Thus, over the past decade particle size-specific sampling of workers in an occupational setting has begun to supplement or replace total mass sampling as it was clearly proven through research that total mass concentration ignored the fact that the deposition site of a particle within the respiratory tract may at times control the extent of the hazard (Lippmann, 1999). At first non-respirable particulates were separated from respirable particulates as research proved that total dust samples overestimated the hazard of the exposure (Vincent, 1999). The increase of knowledge of particulate matter led to the development of a new criteria and approach to particle size-specific sampling. The three different fractions of particulate matter that are applied to occupational hygiene samplings are inhalable (<100 μm), thoracic (<10 μm) and respirable (<4 μm) fractions (Vincent *et al.*, 2001; Vincent, 1999; Phalen, 1999). The inhalable particulates are the particulate mass that can enter the body through breathing and is hazardous when deposited anywhere within the respiratory tract. Thoracic particulate mass is deposited beyond the larynx and in the gas exchange regions. The alveolar region is penetrated by the respirable mass fraction of total dust (Belle & Stanton, 2007; Klaassen & Watkins, 2003; Ramachandran, 1996; Vincent, 1999). Vincent (1999) states that deposition probabilities in each region can be used to relate the anatomical locations of various diseases to the sizes of particles that tend to cause these diseases.

In the mining industry different mining methods are used, materials with different properties are produced, different operational-processing activities exist and atmospheric conditions and locations differ. This means that different sizes of particulates are produced, with different

chemical properties and differ in the impact it would have on the exposed workers' health. In the South African mining sector all operations need to comply with the Department of Minerals and Resources' (DMR) requirements and standards of particulate exposure. However, particulate size is not taken in to consideration when standards and requirements are set. This leads to inaccurate characterization of health risks associated with particulate exposure. Taking the different processes in consideration and investigating the characteristics of the airborne particulates, a more accurate risk assessment could be made. It may also lead to developing process specific standards. If the particle size distribution can be determined for airborne particulates, the respiratory deposition may be anticipated and a more accurate health risk of workers may be established. Sivulka *et al.* (2007) support this by stating that future respiratory-based Occupational Exposure Limits (OELs) will be formulated concentrating solely on the particle fraction that is relevant to the health risks at hand.

In this study nickel is being applied to investigate the characterization of airborne particulate exposure in the platinum processing industry. Although the most common health effect of nickel is contact dermatitis, an allergic reaction of the skin, this study mainly focuses on the exposure to nickel particulates through respiratory inhalation. Nickel compound exposure may lead to an array of adverse health effect through chronic exposure such as lung fibrosis, cardiovascular and kidney diseases (Kasprzak *et al.*, 2003). Nickel's carcinogenic properties are the most important factor in the risk assessment of nickel in an occupational setting. Metallic nickel is classified by the IARC (1997) as a possible human carcinogen (Group 2B) whereas all nickel compounds are seen as carcinogenic to humans specifically for lung, nasal cavity and para-nasal sinuses (Group 1). In the past it was believed that only insoluble nickel had carcinogenic effects on humans, but new research has proven that some soluble compounds may also have carcinogenic effects (Haber *et al.*, 2000; Sivulka, *et al.*, 2007).

Although health effects of nickel and nickel compounds have been a key research topic during the years, most researchers have concentrated on total or just inhalable fraction sampling due to the fact that certain nickel species have been associated with both nasal and lung cancers. The MSHA threshold for soluble nickel is 0.1 mg/m^3 while for insoluble nickel it is set at 1.0 mg/m^3 . In both cases total dust is measured and particle size is not taken into consideration. Sivulka (2005) states that the number of nasal cancer cases has greatly diminished over the past decades, but to what extent lung cancer incidence has declined is not clear. Because of this, the interest in investigating not only the inhalable fraction of

particulate exposure but the thoracic subfractions as well has risen. Such knowledge may lead to possible future respiratory-based OELs for nickel based solely on particles deposited in the trachea-bronchial region of the respiratory tract, rather than particles deposited higher up. There seems to be a lack of knowledge and research on the precise particulate size of nickel particles workers are exposed to, with a small number of studies investigating the potential of particulate size selective sampling in the nickel mining industry. There are also no particulate size data for nickel currently available for the South African mining industry.

This study aims to evaluate and compare two areas of the platinum refining process and identify particulate size exposure of workers in the relevant areas in the South African mining industry.

METHODOLOGY

Two areas of potential worker exposure were investigated through area monitoring. The first area that was evaluated is at the smelter where the matte, the concentrated metal rich part of the ore, is crushed and offloaded before being dispatched to the base metal refinery. Visibly excessive dust particulates are generated in the crushing and offloading process. Workers only spend a short part of an 8-hour shift in this exposure area (to switch machinery on and off and to assist offloading). The crusher also only operates once enough matte has been collected to be crushed. Although the worker is not exposed to the particulates for a full 40 – hour week the exposure of the workers is still worrying as monthly air sampling has shown high levels of insoluble nickel exposure. Thus the crusher area is classified as a mandatory respirator and eye protection zone for all workers commencing work in this area.

The second area was the tankhouse situated at the base metal refineries where nickel is extracted from a nickel sulfate solution by an electrolytic process. The tankhouse is a big building with two open sides and mainly relies on natural ventilation. Polypropylene beads are used to minimize workers' exposure to the nickel mist whilst workers are at close proximity to the nickel solution baths. Although this method reduces the exposure, most mandatory sampling still indicates high exposure levels of soluble nickel. It is also a mandatory respirator, glove and eye protection zone for all workers entering the area. Both areas were divided into three sections where sampling was repeated three times in each section.

Two methods were used to collect particulate samples, NIOSH method 0500 using a 37 mm cassette (for total dust measurement) and MCE (Mixed Cellulose Ester) filter for sampling and the Respicon particle sampler. Instruments were placed in the area of the highest expected particulate exposure next to each other and ran simultaneously for the duration of an 8-hour shift. The highest expected exposure area in the crushers was determined by a walk-through inspection where the source of the highest dust emission was chosen as the sampling area. The tankhouse, however, is a large area. The sampling area was chosen central to the cells that were active for nickel extraction on the day of sampling, for data to be a true replica of workers day-to-day exposure. Four filters (three from the Respicon and one using NIOSH 0500 method) were collected each day. The sampling commenced over 12 days. It will be noticed in the results that there are not always data for 12 filters taking human error in consideration in the sampling and analysis process.

Sampling methods

Respicon particle sampler

The Respicon is a multi-stage, virtual impactor that traps airborne particles onto three individual collection filters. The Respicon uses a single sampling head (inlet has 50% cut-off size of 100 μm) to model the human respiratory tract and simultaneously determine the three critical particle fractions: inhalable (50% cut-off at $> 10 \mu\text{m}$) thoracic (50% cut-off at 10 μm), and respirable (50% cut-off at 4 μm). The mass of deposited particles is determined by comparing the filter weights before and after sampling.

Area monitoring of nickel exposure was carried out in the crusher and tankhouse areas with the aid of a Gilair sampling pump with flexible connecting tubing used at a flow rate of 3.11 l/min in accordance with manufacturers' instructions and pre-weighed mixed ester cellulose filters, 37 mm diameter.

Each pump was calibrated using a Gilian Gilibrator air flow calibrator. These filters were weighed after exposure and sent to an accredited laboratory for element composition analysis according to the NIOSH 7300 method. Analysis was done to determine the soluble nickel concentration and percentage of soluble nickel present in each stage for the tankhouse samples. In the case of the crusher area, analysis was done for insoluble nickel. Using the formulas provided in the Respicon manual two additional particle-size fractions (extra-thoracic and trachea-bronchial fractions) could be calculated.

Table 1. Respicon formulas to calculate the different fractions.

Fraction	Formula
Respirable fraction	$C_{\text{resp}} = (m1)*1000/(Q1)*ts$
Thoracic fraction	$C_{\text{thor}} = (m1+m2)*1000/(Q1+Q2)*ts$
Inhalable fraction	$C_{\text{inh}} = (m1+m2+m3)*1000/(Q1+Q2+Q3)*ts$
Extra-thoracic fraction	$C_{\text{exth}} = C_{\text{inh}} - C_{\text{thor}}$
Tracheo-bronchial fraction	$C_{\text{tb}} = C_{\text{thor}} - C_{\text{resp}}$

Terms: C_{resp} - respirable fraction (mg/m³); C_{thor} - thoracic fraction (mg/m³); C_{inh} - inhalable fraction (mg/m³); C_{exth} - extra-bronchial fraction (mg/m³); C_{tb} - tracheo-bronchial fraction (mg/m³); m1 - mass deposited on filter #1 (mg); m2 - mass deposited on filter #2 (mg); m3 - mass deposited on filter #3 (mg); Q1 - flow rate through filter #1 (2.66 Lpm); Q2 - flow rate through filter #2 (0.33 Lpm); Q3 - flow rate through filter #3 (0.11 Lpm); ts - sample duration (minutes).

NIOSH 0500 – 37 mm cassette (for total dust measurement) cassette and MCE filter assembly

Area monitoring of nickel exposure was carried out in the crushing and tankhouse areas with the aid of a Gilair sampling pump operating at the flow rate of 2 l/min according to manufacturer’s instructions with flexible connecting tubing and pre-weighed mixed ester cellulose filters, 37 mm diameter.

Particulate size distribution

Each sampling pump was calibrated using a Gilian Gilibrator air flow calibrator. Particulate size distribution was determined and depicted as cumulative percentages (D10, D50 and D90) using the CSIR (Council for Scientific and Industrial Research) method 16916-1 based on the ASTM (American Society for Testing and Materials) C1070-01 method which is a standard test method for determining particle distribution using laser scattering instrumentation.

Statistical analysis

Descriptive statistics with confidence intervals were performed. A *t*-test for independent groups was used to compare the particle concentration, nickel percentages and particle fractions of the two exposure areas for statistical significance. The non-parametric Mann-

Whitney U-test was used to compare the particle size of the two exposure areas for statistical significance. All data with a P-value of ≤ 0.05 are considered to be significant.

RESULTS

The particle mass concentration, nickel mass percentages, particle size distribution and particle size fractions were determined for the crusher and tankhouse area. All statistical results will be discussed in the next few paragraphs.

In Table 2 the basic statistical data are depicted for the tankhouse and crusher areas which include the means, number of samples taken; minimum and maximum values of the two areas.

From Fig. 1 it is clear that the mean particle mass concentration of the crusher area is much higher than that of the tankhouse area, with the mass concentration of 4 μm being 28 times higher, 10 μm 31 times higher and > 10 μm 29 times higher. The total dust concentration for the tankhouse is 5.96 mg/m^3 consisting of 9.7% 4 μm particles, 28.02% 10 μm particles and 62.25% of > 10 μm particles. The crusher area however has a higher total dust concentration of 174 mg/m^3 consisting of 9.21% 4 μm particles, 29.22% of 10 μm particles and 61.57% of > 10 μm particles.

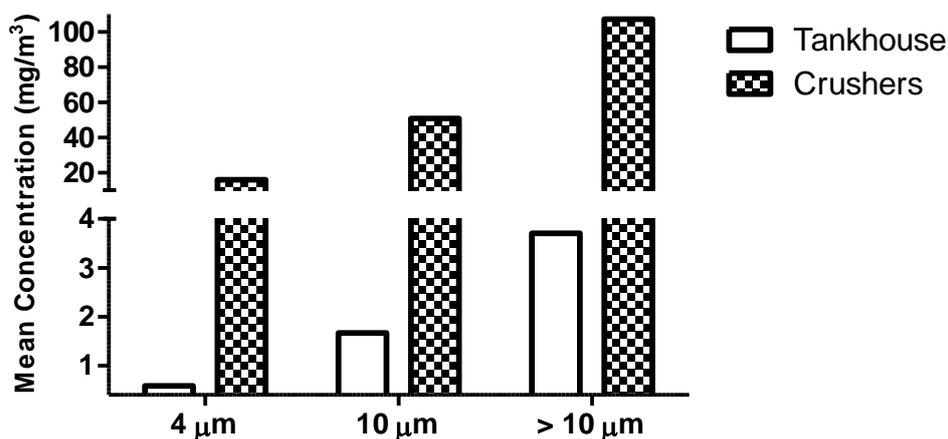


Fig 1. Mean particle concentrations of the tankhouse and crusher areas as measured by the Respicon sampler.

A *t*-test for independent groups was used to compare the two particle concentrations of the two areas. There are highly statistical significant differences between the mean sample

concentrations of the tankhouse and crushers area for all three cut-off sizes (4 μm : $P = 0.003$; 10 μm : $P = 0.002$; >10 μm : $P = 0.003$).

The mean nickel percentages of the different cut-off sizes for the crushers are significantly higher than that of the tankhouse area, as shown in Fig. 2. Highly statistical significant differences between the three cut-off sizes of the two areas were determined using a t -test for independent groups (4 μm : $P < 0.001$; 10 μm : $P < 0.001$; >10 μm : $P < 0.001$). The nickel percentage values of the different cut-off sizes of the same area - tankhouse (4 μm : 10.24%; 10 μm : 14.62%; >10 μm : 15.34%) and crushers (4 μm : 72.17%; 10 μm : 72.46%; >10 μm : 69.47%) are in close range.

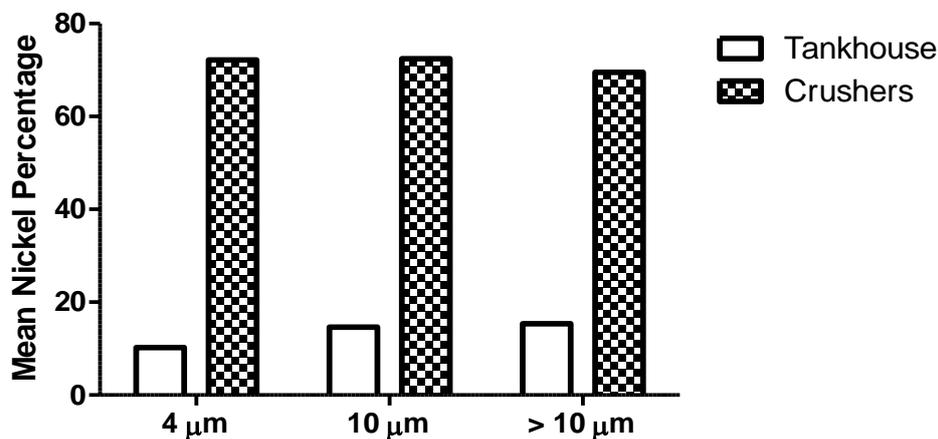


Fig. 2. Mean nickel percentage present in the different fractions of the tankhouse and crusher areas as measured by the Respicon sampler.

Table 3 depicts the degrees of freedom and t -(based on separate variance estimate) values for the sample concentrations and nickel percentages of the two areas. The degrees of freedom values are associated with the size of the groups. The bigger the group the higher the df value will be and the easier significant differences can be demonstrated. The separate variance estimate values, however, are a t -value where it was not assumed that the standard deviations would be equal.

The comparison of the mean particle size distribution of the tankhouse and crusher area is shown in Table 2 and Fig. 3. D10, D50 and D90 are expressed as cumulative percentages with D10, D50 and D90 indicating that 10% of the sample is smaller than 1.89 μm , 50% of

the sample is smaller than 7.29 μm and 90% of the sample is smaller than 28.36 μm for the tankhouse. The crusher results indicate that 10% of the sample is smaller than 7.54 μm ; 50% is smaller than 16.03 μm and 90% is smaller than 1041.98 μm . The high value of 1041.98 μm may be due to the excessive dust particulates generated in the crushing and offloading process.

Table 3. Particle concentration and nickel percentage degrees of freedom and t-separate variance estimate values of the tankhouse and crushers areas.

Sample concentration	<i>df</i>	<i>t separ. var. est.</i>	<i>P</i>
4 μm	11.056	-3.77	0.003
10 μm	11.012	-3.93	0.002
> 10 μm	11.013	-3.78	0.003
Nickel percentage	<i>df</i>	<i>t separ. var. est.</i>	<i>P</i>
4 μm	8.271	-5.60	< 0.001
10 μm	8.09	-7.99	< 0.001
> 10 μm	8.047	-5.67	< 0.001

df: degrees of freedom; *t separ var est*: t-value based on separate variance estimates.

The Mann-Whitney test was used to determine the statistical difference between the two areas due to the occurrence of outliers in the one locality. There are highly statistical significant differences between two of the size distribution values of the two areas (D10: $P = 0.004$; D50: $P = 0.004$) with differences between D90 leaning towards being statistical significant ($P = 0.061$).

The Z-value and rank sum values of both the tankhouse and crusher area for the different cumulative percentages of the particle sizes are shown in Table 4. The Z and rank sum values are recorded due to the fact that the Mann-Whitney U test for non-parametric data was used to determine statistical significance between the tankhouse and crusher areas.

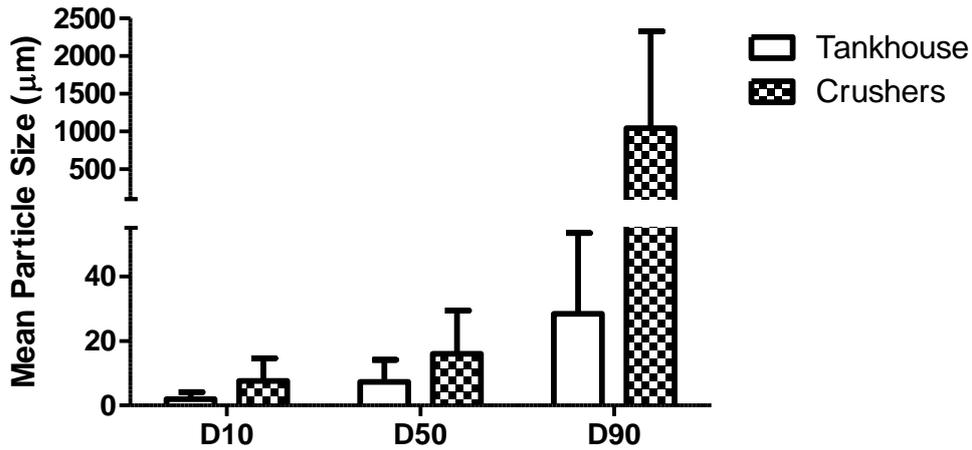


Fig. 3. Mean particle size of the tankhouse and crusher areas measured using the NIOSH 0500 method with 37 mm cassette for total dust and MCE filter assembly and analysed by laser scattering instrumentation.

Table 4. Z and rank sum values for the different cumulative percentages of the particles sizes in the tankhouse and crusher areas.

Cumulative percentage of the particle size	Z-value	Rank Sum		P
		Tankhouse area	Crushers area	
D10	-2.86	100.0	200.0	0.004
D50	-2.08	113.5	186.5	0.004
D90	-1.88	117.0	183.0	0.061

In Table 2 and Fig. 4 it can be seen that the mean inhalable fraction is the highest for both the tankhouse (4.95 mg/m³) and the crusher (106.8 mg/m³) areas. The inhalable fraction concentration in the crusher area being more than 20 times higher than in the tankhouse area.

Table 2. Summary of the descriptive statistical data for the tankhouse and crusher areas.

Tankhouse area					Crushers area				
RESPICON PARTICULATE SAMPLER									
Particle mass concentration	N	Mean (mg/m ³)	Min (mg/m ³)	Max (mg/m ³)	N	Mean (mg/m ³)	Min (mg/m ³)	Max (mg/m ³)	<i>P-value</i>
4 µm	10	0.58	0.14	2.33	12	16.04	0.51	41.65	0.003
10 µm	10	1.67	0.66	3.22	12	50.88	1.22	132.17	0.002
> 10 µm	10	3.71	1.53	8.32	12	107.2	2.16	282.45	0.003
Nickel mass percentage	N	Mean (mg/m ³)	Min (mg/m ³)	Max (mg/m ³)	N	Mean (mg/m ³)	Min (mg/m ³)	Max (mg/m ³)	<i>P-value</i>
4 µm	8	10.24	0.2	16	9	72.17	8.63	97.07	< 0.001
10 µm	8	14.62	12	14.46	9	72.46	26.84	97.37	< 0.001
> 10 µm	8	15.34	2.26	17.4	9	69.47	1.28	92.05	< 0.001
Particle fractions	N	Mean (mg/m ³)	Min (mg/m ³)	Max (mg/m ³)	N	Mean (mg/m ³)	Min (mg/m ³)	Max (mg/m ³)	<i>P-value</i>
Respirable fraction	11	1.64	0.13	1.93	12	16.00	0.51	41.55	0.004
Thoracic fraction	11	2.46	0.64	2.73	12	50.69	1.22	131.74	0.001
Inhalable fraction	11	4.95	1.51	8.26	12	106.8	2.16	281.45	0.002
Extra-thoracic fraction	11	2.48	0.85	5.65	12	56.11	0.94	192.54	0.008
Tracheo-bronchial fraction	11	1.05	0.4	1.98	12	34.69	0.71	90.19	0.001
NIOSH 0500 METHOD WITH 37 mm CASSETTE FOR TOTAL DUST AND MCE FILTER ASSEMBLY									
Particle size analysis	N	Mean (micron)	Min (micron)	Max (micron)	N	Mean (micron)	Min (micron)	Max (micron)	<i>P-value</i>
D10	12	1.89	0.1	6	12	7.54	1.1	20.5	0.004
D50	12	7.29	0.3	19.9	12	16.03	5.7	44.3	0.004
D90	12	28.36	2.5	74.7	12	1041.98	44.3	2693.5	0.061

In Table 5 is indicated that the paired Student's *t*-test indicated highly statistical significant differences between all the fractions of the two areas (respirable: $P = 0.004$; thoracic: $P = 0.001$; inhalable: $P = 0.002$; extra-thoracic: $P = 0.008$; trachea-bronchial: $P = 0.001$).

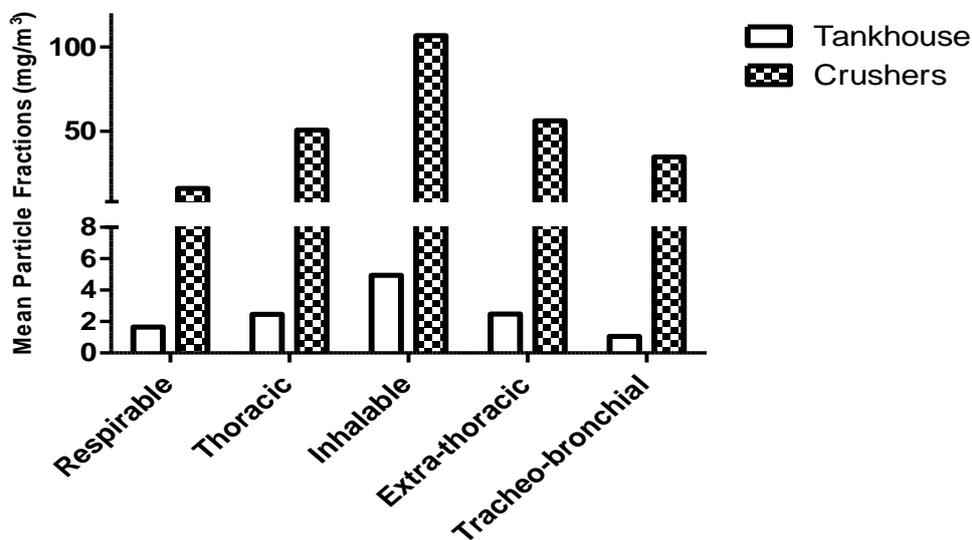


Fig. 4. Mean particle fractions of the tankhouse and crusher areas as measured by the Respicon sampler.

The degrees of freedom and *t*-values (based on separate variance estimate) for the particle fraction comparison of the tankhouse and crusher areas are depicted in Table 5.

Table 5. Tankhouse and crusher areas degrees of freedom and *t* –values (based on separate variance estimate) for the different fractions.

Sample concentration	<i>df</i>	<i>t separ. var. est.</i>	<i>P</i>
Respirable fraction	12.61	-3.39	0.004
Thoracic fraction	11.12	-3.86	0.001
Inhalable fraction	11.05	-3.73	0.002
Extra-thoracic fraction	11.02	-3.07	0.008
Tracheo-bronchial fraction	11.01	-3.83	0.001

df: degrees of freedom; *t separ. var. est.*: *t*-value based on separate variance estimate.

DISCUSSION

From the results reported on the tankhouse it can be seen that the highest level of exposure is to particulates bigger than 10 μm and a total concentration of 5.96 mg/m^3 . Comparing these findings with the Mine Health and Safety Act (MHSA) threshold for soluble nickel, which is 0.1 mg/m^3 , soluble nickel exposure is a definite concern. The nickel percentage is also the highest for particulates 10 μm and bigger, there is, however, high nickel percentages for the entire particle sizes collected. This indicates that all three cut-off sizes consist between 10 and 20% out of soluble nickel particles. Particle size data show that 90 % of the particulates sampled are smaller than 28.358 μm with the particle fraction data declaring that the highest level of exposure is to the inhalable fraction. The thoracic and extra-thoracic fractions are second highest and may be valuable knowledge when assessing the health risk of the exposure in this area. One can now state that the particulates in the tankhouse area fall mainly under the inhalable fraction. It indicates that most particles exposed to do not enter the respiratory system beyond the head airway region.

The sample concentration for the crusher area was the highest for particulates bigger than 10 μm , with the nickel percentage the highest for particles with a cut off-size of 10 μm . The total concentration being 174 mg/m^3 , which is much higher than the MHSA threshold for insoluble nickel exposure (1 mg/m^3). It must be highlighted that the nickel percentages for all three cut-off sizes lies between 92.05 and 97.37%, indicating a very equal nickel percentage across the three particle sizes. This indicates that the particulates workers are exposed to mainly consist of insoluble nickel. The particle distribution shows that 90% of the particulate exposure is to particles smaller than 1041.983 μm . The inhalable fraction is the highest for the crusher area, with the thoracic and extra-thoracic fractions second highest and almost equal. Thus, the highest level of exposure in the crusher is to inhalable particulates. Inhalable particulates are deposited mainly in the head airway region.

After comparing the tankhouse and crusher areas, it is clear that the crusher area has the highest level of particulate exposure across the sampling methods used. The crusher also has the highest inhalable particulate exposure to insoluble nickel. The nickel content and particle size of both areas are of concern because nickel compounds are classified as a human carcinogen specifically for lung, nasal cavity and para-nasal sinuses by the IARC (1997).

In a review study by Sivulka *et al.* (2007), particle size selective sampling for the different nickel species is emphasized. Nickel species are produced when nickel combines with other

elements forming different nickel compounds or species each with their own physiochemical properties and biological effects (Öller, 2002). The purpose of the article was to review the basis for setting inhalable occupational exposure standards. It is noted that the most particle size-selective distribution data have been collected using either the Institute of Occupational Medicine (IOM) Personal Inhalable Dust Spectrometer or a modified Andersen cascade impactor used as a stationary area sampler. It is important to note that most of the data in the studies reviewed by Sivulka were obtained through personal sampling and a few by using mannequins, whereas area sampling was conducted in this study. The findings of the tankhouse and crusher areas in this study indicate much higher exposure to inhalable nickel particulates than that of the data reported by Sivulka *et al.*, (2007). This difference in findings may be due to the fact that a Respicon sampler was used in this study to determine the particle size distribution. Further research in comparing these two samplers in the nickel industry may confirm this. Research conducted in a Russian electrorefining area shows an average inhalable nickel concentration of 0.34 mg/m^3 , while in Norway a study found the average inhalable nickel particle exposure to be 0.059 mg/m^3 using a IOM sampler for sample collection. The crusher area findings in this study were at a much higher level than that of previous research done in similar areas. For example a Canadian study found the following average inhalable nickel particle exposures: Company A - matte crushing: 0.47 mg/m^3 ; matte processing: 1.91 mg/m^3 ; Company B – feed preparation: 0.151 mg/m^3 ; matte room: 0.169 mg/m^3 . Findings in Norway indicate an average value of 0.478 mg/m^3 for inhalable nickel particulates. Once again it must be noted that personal sampling was conducted in these studies using an IOM sampler. For both the tankhouse and crusher areas much higher values were reported. Factors such as the difference in operations and processes in different industries and countries, different sampling methods and personal or area sampling need to be taken in consideration when comparing data with findings from other studies. If findings from the crushers and tankhouse area are compared the difference in particle mass concentration and nickel percentages are obvious, making it clear than no two areas will have the same nickel exposure. Thus, it may also indicate the inaccuracy of using standard exposure limits across different industries if particle size and sampling methods are not taken into consideration.

In this study the Respicon was used to collect data to determine the sample concentrations and nickel percentages and particle fractions for both areas. The benefit of the Respicon is that three particle fractions ($4 \mu\text{m}$, $10 \mu\text{m}$ and $> 10 \mu\text{m}$) could be collected simultaneously

using only one instrument. For this study only area sampling was done. More research needs to be done on personal Respicon sampling in the tankhouse and crusher areas. One difference Brouwer *et al.* (2006) found in the data retrieved from the Respicon was when compared to data collected with the IOM MultiDust sampler, the Respicon findings were lower for both the inhalable and thoracic fractions. It needs to be taken in consideration that the number of measurements in Brouwer *et al.* (2006) was limited, and findings are only indicative. Bråtveit *et al.* (2004) reported significantly higher concentrations for the conventional IOM sampler compared to the Respicon for the inhalable fraction. More research will need to be done to determine how the Respicon sampler compares with the conventional IOM sampler and IOM MultiDust sampler, especially in the nickel industry, if particle size exposure standards are to be set for future sampling regulations.

Sivulka *et al.* (2007) state that the particle size specific approach of the American Conference of Governmental Industrial Hygienists (ACGIH) has not been widely adopted by regulatory bodies and standard committees. A reason may be economical expenses of acquiring the necessary particle size samplers and the analysis that needs to be done for all nickel species across all sites of an operation. However, Vincent *et al.* (2001) and Kerr *et al.* (2001) proved in recent nickel industry based studies that it is possible to develop a “fingerprint” of a worksite that includes information on the species and particulate sizes present at a particular site. In these studies it was proved that nickel species present in different workplace operations were distributed uniformly across the whole range of particles. Different scenarios might apply to other sectors where different nickel specie concentrations may be detected in each of the three particle size selective sampling levels (4 µm, 10 µm and > 10 µm). Once such a “fingerprint” is established, occupational hygienist may routinely estimate workers exposure to individual nickel species fractions based on measurement only of overall inhalable nickel. Speciation and particle size analysis may only be necessary when changes are made to operations of a site or once every season, as atmospheric changes take place.

CONCLUSION

The data obtained through this study is invaluable in the process of changing the way the mining industry assesses workers particulate exposure. It is clear that it is possible to determine the particulate size workers are exposed to. The Respicon has also proven to be an easy and user friendly device to use in determining particle size fractions. Classification of health-risks may also be reviewed when based on particle specific sampling. This may be

true not only for nickel exposure but for other particulate exposures as well. The findings give insight into necessary factors such as differences in particulate exposure levels between areas within one industry, different sampling methods that may be used and the possible importance of specification of nickel particulate exposure that need to be taken into consideration when OELs and standards are established within industries. It is also clear that more research needs to be done on the particle size distribution of nickel and nickel compound exposure in the nickel producing industry before any particle size-selective sampling programme can be implemented seeing that the mining industry in South Africa has not yet moved towards particle size selective sampling and a thorough research study needs to be launched to act as a flagship study where all the findings of studies such as this one are taken in consideration. More research will also be needed before any standard committee will implement size-selective OELs in the mining industry. It may be of great benefit to conduct a study where area sampling is done in conjunction with personal sampling. This will give a greater understanding of the exact particle size workers are exposed to.

In the meantime, the findings of this study may be used by the employer to re-evaluate the workers exposure seeing that particulate size of nickel in both areas has not been determined before this study. Results on particulate fractions give the employer the necessary insight into particle exposure of the workers in the two areas and may be included in the risk assessments of both areas. Additional information with regards to the particle fractions gathered by the Respicon sampler indicates that thoracic and extra-thoracic particulates are in close range of the inhalable fractions – for both areas. This may help the employer to revise the current control measures in place, seeing that the inhalable, thoracic and extra-thoracic fractions were seen as concerns. It is also recommended to revise the specifications of the personal protection equipment being supplied to the workers. Knowing the particulate size exposure may assist the employer in choosing the personal protection equipment more accurately; making sure that the respirator filter being used can withstand the specific particulate size load the workers are exposed to.

It may be useful for future research to determine the exact nickel species present in each particle fraction, to make an even better, more accurate health-based evaluation of workers' exposure.

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CHAPTER 4: CONCLUDING CHAPTER

4.1 SUMMARY

The aims and objectives of this study were to characterize and compare the airborne particulate matter in the tankhouse and crusher areas of a base metal refinery sampled with two separate methods, in terms of mass concentration, nickel content, and particle size distribution. The results showed that the highest level of exposure in the tankhouse was to particulates bigger than 10 μm and had a total concentration of 5.96 mg/m^3 . Comparing these findings with the MSHA threshold for soluble nickel, which is 0.1 mg/m^3 , soluble nickel exposure is a definite concern. The nickel percentage was also the highest for particulates 10 μm and larger. High nickel percentages were collected for all the particle sizes. This indicated that all three cut-off sizes consisted out of between 10 and 20% soluble nickel particles. Particle size data showed that 90% of the particulates sampled were smaller than 28.358 μm with the particle fraction data declaring that the highest level of exposure was to the inhalable fraction. The thoracic and extra-thoracic fractions were second highest and are important when assessing the health risk of the exposure in this area. It can now be concluded that the particulates in the tankhouse area are mainly inhalable which does not enter the respiratory system beyond the head airway region.

The sample concentration for the crusher area was the highest for particulates bigger than 10 μm , with the nickel percentage the highest for particles with a cut off-size of 10 μm . The total concentration was 174 mg/m^3 , which was much higher than the MSHA threshold for insoluble nickel exposure (1 mg/m^3). It must be highlighted that the nickel percentages for all three cut-off sizes were between 92.05 and 97.37%. The particle distribution showed that 90% of the particulate exposure was to particles smaller than 1041.983 μm . The inhalable fraction was the highest for the crusher area, with the thoracic and extra-thoracic fractions second highest and almost equal. Thus, the highest level of exposure in the crusher is to inhalable particulates which are deposited mainly in the head airway region.

After comparing the tankhouse and crusher areas, it is clear that the crusher area has the highest level of particulate exposure across the sampling methods used. The crusher also has the highest inhalable particulate exposure to insoluble nickel. The nickel content and particle size of both areas are of concern because nickel compounds are classified as a human carcinogen specifically for lung, nasal cavity and para-nasal sinuses by the IARC (1997).

The hypothesis of this study was that there is a significant difference in the airborne particulate matter found in the tankhouse and crusher areas in terms of the particle mass concentration, nickel content, and particle size distribution. The hypothesis can be accepted. The exposure to airborne particulate matter of the two areas were significantly different, with the highest exposure level being in the crusher area. The findings also indicated that workers in both the areas are mostly exposed to the inhalable, thoracic and extra-thoracic particulate fractions.

4.2 LIMITATIONS AND FUTURE PROSPECTS

A few limitations within this study were evident after assessing the results. It would've been of great value if the exact nickel species for every particle fraction was determined. This would give a greater understanding of the biological pathway through which the nickel particle can enter the respiratory system and what exact health effect may be elicited. Highlighting the differences of the nature and potency of the effects of different nickel species on the respiratory tract and the respiratory health of the worker may be helpful as an evaluation tool of the health risks in the future.

Area sampling was conducted in this study. The ideal would be to conduct a study where both area and personal sampling is conducted and compared. This would help determine if area sampling is a true recollection of the workers particulate exposure in the workplace.

More extensive research also needs to be done on the Respicon and its application in the mining industry. It may be a viable study to compare the Respicon sampler with, for example, the conventional IOM sampler in different scenarios and different chemical exposures across the processing plants to determine a more accurate application basis for future use as a sole particle fraction determinant.

4.3 RECOMMENDATIONS

From the findings of this study the basis for a particle size selective sampling program in the nickel processing industry may be determined and implemented to reduce workers exposure

levels to the particular particulates. The results may also be used to re-evaluate and update the current risk assessments for both the areas investigated.

Workers needs to be educated on the particle size exposure of both areas and the exact way particles are distributed in the respiratory tract. This may contribute to a better informed worker that understands the logic behind wearing the specific personal protective equipment required.

Now that the particle size exposure of the workers is known, the personal protective equipment in use may also be re-evaluated. This will make sure that the model of respirator used in the areas is adequate to collect the specific particle size of the nickel workers are exposed to. It will also determine if the gloves and coveralls are made of adequate material. Many manufacturers may find these findings useful when designing new protective gear. The metallurgical and engineering departments may use particulate size determination in the design of control measures and in the design of production systems to retrieve the optimum amount of nickel possible.

It may be useful to discuss the particle size exposure data with the health and safety board to indicate the extent of the workers exposure and emphasize the efficiency of the current control measures that are in place. It may also be used to validate economical input needed to upgrade the current areas to lower workers exposure levels.

Particle size selective sampling has been widely adopted in the world but to a lesser extent in South Africa. These findings may be a helpful tool to move towards the international standards of classifying exposure levels according to particle sizes and health related OELs.