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Dermal and respiratory exposure to cobalt salts in a packaging area of a base metal refinery

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Preface

The article format was chosen for this mini-dissertation. The article is written according to the requirements of the journal Annals of Occupational Hygiene. The journal requires that references should be listed in alphabetical order by name of first author, using the Vancouver Style of abbreviation and punctuation.

Author's contributions

This study was planned and executed by a team of researchers. The contribution of each of the researchers are:

Mr. J. du Plessis

- Supervisor
- Assisted in the introduction, designing, planning and reporting of the study
- Approval of the protocol
- Professional input and recommendations
- Reviewing of the mini-dissertation and documentation of the study

Prof. F. Eloff

- Co-supervisor
- Assisted with the planning of the study
- Assisted with the planning and approval of the protocol
- Professional input and recommendations
- Reviewing of the mini-dissertation and documentation of the study

L van der Westhuizen

- Planning and protocol of the study
- Dermal, respiratory and surface sampling
- Skin condition measurements
- Literature research
- Statistical analysis and interpretation of the results
- Recommendations
- Writing of the article

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 Lelani van der Westhuizen's M.Sc (Occupational Hygiene) mini-dissertation.

_____	_____
Mr. J.L. du Plessis	Prof. F.C. Eloff
(Supervisor)	(Co-Supervisor)

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List of abbreviations

(ACD)	Allergic Contact Dermatitis
(ANOVA)	Analysis of Variance
(CCOHS)	Canadian Centre for Occupational Health and Safety
(CDI)	Cobalt Development Institute
(IARC)	International Agency for Research of Cancer
(ICP-AES)	Inductively Coupled Plasma – Atomic Emission Spectrometry
(IOM)	Institute of Occupational Medicine
(NIOSH)	National Institute for Occupational Safety and Health
(NPI)	National Pollutant Inventory
(NTP)	National Toxicological Program
(OEL)	Occupational exposure limit
(OSHA)	Occupational Safety and Health Administration
(PPE)	Personal protective equipment
(REACH)	Registration, Evaluation, Authorisation and Restriction of Chemicals Regulation of the European Union
(RLTFs)	Respiratory lining tract fluids
(RTECs)	Respiratory tract epithelial cells
(SC)	Stratum corneum
(Std-Co)	Standard cobalt
(STEL)	Short-term exposure limit
(TEWL)	Transepidermal water loss
(TWA)	Time weighted average
(Uf-Co)	Ultra fine cobalt

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ABSTRACT

Cobalt is a commonly known sensitiser in industrial settings and has been classified by the IARC as a possible group (2B) human carcinogen. Workers at a South African base metal refinery are potentially exposed to cobalt in the cobalt packaging area. The respiratory and dermal exposure to cobalt is a possible health risk. Quantifying the exposures levels assists in determining the degree of the risk as well as the management thereof. The objectives of this study were to assess dermal and respiratory exposure of workers at a cobalt packaging area and to assess their skin condition by measuring transepidermal water loss (TEWL) and skin hydration indices. The skin hydration index was measured on the back of the hand, forehead, wrist and palm at the start, during and end of the shift. The TEWL index was measured at the start and end of the shift on the same areas as the hydration index. Ghostwipes™ was chosen as preferred wipe sampling media to collect dermal and surface samples. Wipe samples were also taken on suspected contaminated workplace surfaces. Respiratory samples were taken by using the Institute of Occupational Medicine (IOM) inhalable aerosol sampler at a flow rate of 2 l/min. Wipes and respiratory samples were analysed for cobalt according to NIOSH method 9102 using inductively coupled plasma-atomic emission spectrometry (ICP-AES). The hydration indices indicated that worker's skin are slightly dry to normal at the beginning of the shift. Hydration on the wrist increased significantly during the shift. TEWL indices increased significantly on the back of the hand, wrist and forehead during the shift. TEWL indices of the palm showed a low barrier function before the shift and deteriorated further to a very low barrier function at the end of the shift. Significant dermal cobalt loading occurred on the back of the hand, forehead, wrist and palm during the shift. The palm was the most exposed and the forehead least. The barrier function of the skin is most likely to be affected by exposure to cobalt. The skin condition of workers put them at greater risk to develop adverse health effects of cobalt. Workplace surfaces were contaminated with cobalt. Airborne cobalt was visible at different working stations. Cobalt exposure is due to numerous sources in the packaging area, thus contributing to the dermal exposure. Respiratory exposure exceeded the 8 hour occupational exposure limit for most of the workers. The guidance limit for short term exposure was exceeded by half of the workers. It is important to minimise the exposure to cobalt in packaging area. Manifestation of the adverse health effects are usually not visible in the short term, the necessary precautions have to be taken to protect the workers.

Keywords: cobalt, dermal, barrier function, hydration, respiratory.

OPSOMMING

Kobalt is ‘n alombekende sensitiseerder in industrieë en is ook geklassifiseer deur die IARC as ‘n moontlike menslike karsinogeen. In ‘n bekende Suid-Afrikaanse onedel metaal rafinadery word die werkers in die kobalt verpakkings area moontlik aan kobalt blootgestel. Die dermale en respiratoriese blootstelling hou ‘n moontlike gesondheidsrisiko in. Deur die hoeveelheid kobalt blootstelling te kwantifiseer, kan die mate van die gesondheidsrisiko bepaal en ook bestuur word. Die doel van die studie is om die dermale en respiratoriese blootstelling van werkers te assesseer, asook die vel kondisie te bepaal deur die hidrasie en transepidermale water verlies (TEWL) te meet. Die vel hidrasie indeks van die bo-kant van die hand, voorkop, gewrig en palm is voor, gedurende en aan die einde van die skof gemeet. Die TEWL indeks is gemeet voor en na die skof op dieselfde areas as die hidrasie indeks. Ghostwipes™ is gebruik as ‘n moniterings media om die hoeveelheid kontaminante op die vel te bepaal. Werksoppervlaktes waar werkers moontlik blootgestel kan word aan kobalt is ook gemoniteer vir moontlike kontaminasie. Respiratoriese monsters is geneem deur van die Institute of Occupational Medicine (IOM) se inasembare monsternemer gebruik te maak. Die persoonlike moniterings pompe is teen 2 l/m gekalibreer. Die dermale en respiratoriese monsters is geanaliseer volgens NIOSH metode 9102. Die hidrasie indeks het aangetoon dat werkers se velle effens droog tot normaal is aan die begin van die skof. Hidrasie vlakke op die gewrig het statisties betekenisvol verhoog gedurende die skof. Hidrasie het wel ‘n impak op velabsorpsie deurdat dit die omskakeling van kobalt na absorbeerbare ione verhoog. TEWL indekse toon aan dat die velbeskermingsfunksie op die bo-kant van die hand, gewrig en voorkop betekenisvol verhoog het aan die einde van die skof. Die velbeskermingsfunksie van die palm was laag voor die skof en het verder afgeneem tot baie laag aan die einde van die skof. Kobalt op die vel oppervlakte van die bo-kant van die hand, gewrig, voorkop en die palm het toegeneem gedurende die skof. Die velbeskermingsfunksie word waarskynlik beinvloed deur die blootstelling aan kobalt**.** Die vel kondisie van die werkers verhoog hul risiko om geaffekteer te word deur die gesondheids effekte van kobalt. Werksplek oppervlaktes is gekontamineer deur kobalt. Vanuit observasies kan gesien word dat groot hoeveelhede luggedraagde kobalt teenwoordig is in die area. Die kobalt blootstelling is afkomstig van verskeie bronne in die verpakkings area wat dus bydrae tot meer blootstelling. Respiratoriese blootstelling van meeste werkers oorskry die beroepsblootstellings drempel vir kobalt. Die aanbevole drempel vir kort termyn blootstelling is ook oorskry by helfte van die werkers. Dit is belangrik dat die kobalt blootstelling in die verpakkings area aansienlik verlaag moet word. Kobalt se gesondheids effekte kan

eers oor ‘n langtermyn manifesteer, nodige beheermaatreëls moet geïmplimenteer word om persoonlike kobalt blootstelling te verlaag.

Sleutel woorde: kobalt, dermale, velbeskermingsfunksie, hidrasie, respiratories.

CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

Workers at a base metal refinery are potentially exposed to cobalt sulfate dust during product packaging tasks. Cobalt sulfate is a water-soluble salt, which has a range of uses in the industrial and agriculture settings. Cobalt and its compounds are classified by the International Agency for Research on Cancer (IARC) as a possible (group 2B) human carcinogen. The IARC reported an increased lung cancer risk associated with long-term respiratory exposure of cobalt dust taking into account potential confounding by smoking and other occupational carcinogens (IARC, 2006). Cobalt is an important skin sensitiser, however little information is known about cobalt skin exposure and causes of cobalt skin sensitisation (Julander *et al.,* 2009).

According to the Mine Health and Safety Act, 1996 (Act no. 29 of 1996) of South Africa (1995), Occupational Hygiene Regulation, the 8 hour occupational exposure limit (OEL) for cobalt and cobalt-compounds is 0.05 mg/m^3 with no skin notation.

Exposure to metals can occur through different exposure routes, of which inhalation have been seen traditionally as the most important route of exposure in terms of potential toxicity (Cherrie *et al*., 2006). Occupational dermal exposures are now receiving more attention, since many substances have the ability to penetrate the skin and cause systemic and local effects (Fenske, 2000).

The movement of a metal particulate through a biological membrane is specific to the type of element as well as the chemical properties of the specific species (Hostynek, 2003). By using the *in vitro* Franz cell system Larese Filon *et al*. (2004, 2007) showed that cobalt powders dissolved in synthetic sweat can release metallic ions, which permeate the skin. Studies also proved that cobalt powders permeate to a greater extent through damaged skin than intact skin (Larese Filon *et al*., 2009). Dermal exposure may be due to direct contact such as immersion or spillage, indirect contact with contaminated surfaces and may be transported to the skin as a vapour or aerosol (Belle and Stanton, 2007).

Various methods exist to assess dermal exposure, which can be categorised into three groups: 1) interception methods (surrogate skin methods), 2) *in situ* detection methods (fluorescent tracer methods) and 3) removal of contaminant methods (Fenske, 1993, Brouwer *et al*., 2000, Cherrie *et al.*, 2000, Souter *et al*., 2000). The removal of contaminant methods, removes contaminants from the skin surface (wiping, washing/rinsing, tape stripping of the skin or other specialised removal

devices) which represent an estimate of exposure, at the time of sampling. Ghostwipes™ sampling media are used for removal of skin contaminants. It has a removal efficiency of >90%. The removal of contaminant method with Ghostwipe™are efficient, and exposure per surface area (µg/cm^2) can be calculated (OSHA, 2002).

The hydration of the stratum corneum (SC) is an important factor in regulating the complex functions of the SC. Retention of water in the SC is dependant on two components: 1) the natural hygroscopic agents present within the corneoytes (known collectively as natural moisturizing factors) and 2) the SC intercellular lipids arranged in a orderly fashion to form the barrier function. Water can escape through the skin by evaporation leaving the skin dehydrated and exposed to exogenous factors (Mundlein *et al*., 2008).

Measurement of the transepidermal water loss (TEWL) indicates the integrity of the skins barrier function. A good barrier function protects the integument system from absorbing potentially harmful substances into the human body where it can act locally or systemically. The hydration levels and TEWL measurement can give a good indication as to the skin's defensive ability against exogenous factors (Verdier-Sévrain and Bonté, 2007).

Cobalt skin exposure in different occupations has been assessed by a few authors (Larese Filon *et al*., 2004, Liden *et al*., 2008, Julander *et al*., 2009), but none have done a study in a base metal refinery. Liden *et al*. (2008) studied exposure of nickel, chromium and cobalt of workers who come into contact with metallic items. Julander *et al*. (2009) found that small concentrations of cobalt are able to elicit allergic contact dermatitis in sensitised persons. Many cobalt respiratory exposure studies have been done, which reported increased risk of developing cancer due to cobalt exposure (Lasfargues *et al*., 1992; Moulin *et al*., 1998; Tüchsen *et al.,* 1996). Little information and research exists concerning the dermal exposure to cobalt, thus further studies related to dermal exposure are important.

1.2 Hypothesis

Workers at a packaging area of a base metal refinery are exposed to cobalt through the dermal and respiratory exposure routes.

1.3 Research aims and objectives

The objectives of this study were to assess dermal and respiratory exposure of workers at a cobalt packaging area of a South-African base metal refinery and to assess their skin condition by measuring transepidermal water loss (TEWL) and skin hydration indices.

1.4 References

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CHAPTER 2

2.1 Introduction

Many metals are known to cause adverse health effects, cobalt is no exception. Not much information concerning the respiratory or dermal exposure of cobalt sulfate is available. It may be due to the limited use of cobalt and cobalt compounds compared to other metals such as platinum, nickel and copper. Many studies focus on the health effects of specific elemental forms of metals, however studies are being extended by many authors to include the other compounds of metal species for example, compounds of cobalt such as cobalt sulfate, cobalt chloride, and tungsten carbide. It has been proved that different compounds of specific metals elicit different effects on human health and it cannot be assumed that all compounds have the same health effect as the elemental form it is joined with. It is also true that certain effects are shared which cannot be ignored.

The aim of this literature study is to discuss the anatomy of the skin and respiratory system, health effects caused by cobalt and occupational exposure studies to cobalt. Many animal, *in situ*, *in vitro* and *in vivo* studies of cobalt compounds have been conducted to explain possible mechanisms of action and health effects.

2.2 Properties of cobalt and cobalt sulfate

Small amounts of cobalt ore is mined for its cobalt content, however it is mostly recovered as a by-product from other mined ores of iron, nickel, copper, silver, manganese, zinc and arsenic (CDI, 2010). Cobalt is widely dispersed and accounts for 0.001 percent of the earth's crust. Cobalt occurs naturally as compounds with arsenic, oxygen and sulfur to form compounds such as cobaltine (CoAsS) and linneite (Co_3S_4) (Barbalace, 2007).

Cobalt's atomic number is 27 and has an atomic weight of 58.9332. The boiling point is 2870 ℃ and has a melting point of 1495 ℃. Two allotropes of cobalt are known: close-packed-hexagonal structure, which is stable below 417 ℃ and the face-centred-cubic, stable at high temperatures. It is ferromagnetic up to the highest known curie point of any metal or alloy at 1121 ℃. This element is one of only three metals, which are ferromagnetic at room temperature. Pure cobalt does not dissolve in water but does react with acids. Cobalt sulfate and cobalt nitrate is able to dissolve in water (NPI, 2009). Cobalt does not combine directly with hydrogen or nitrogen when dissolved slowly in dilute acids but will combine with carbon, phosphorus or sulfur when heated. At high temperatures, oxygen and water vapour will attack cobalt to form cobaltous oxide, CoO (produces a metal in the +2 state) (Encyclopaedia Britannica, 2010). Compounds of cobalt is almost always in a +2 or +3 oxidation and

rarely in states of +4, +1 and -1. Compounds of cobalt which have a state of +2 is called cobaltous and is stable in water. Those compounds having a +3 oxidation state is called cobaltic. Cobaltic compounds of cobalt form more complex ions than any known metal with the exception of platinum. An inorganic salt of divalent cobalt is the sulfate ($CoSO_4$), which is one of the important cobalt salts. A hydrated form of cobalt is cobalt sulfate heptahydrate, a water-soluble cobalt salt. The interaction of cobalt oxide, hydroxide or carbonate with sulferic acid forms cobalt sulfate, 2005).

2.3 Uses of cobalt and cobalt sulfate

Cobalt sulfate has a variety of industrial and agricultural uses. Cobalt is mostly used for the production of super alloys, corrosion resistant alloys, prosthetics, magnets, pigments, paints, dying agents, jewellery (Thyssen *et al*., 2009) as well as diamond polishing and catalysts (De Boeck *et al*., 2003). The electroplating and electrochemical industries have been using cobalt-sulfate as a drying agent in inks, varnishes, and linoleum (NTP, 2005).

2.4 Exposure to cobalt and cobalt sulfate

Occupational exposure to cobalt occurs mainly in industrial refining, in the production of alloys, and in the tungsten carbide metal industry (IARC, 2006). The traditional view is that exposure to cobalt occurs mainly through inhalation and skin contact. Occupational exposure to cobalt may bring forth adverse health effects in different tissues and organs, such as the respiratory tract, skin, the hemapoietic tissues, the myocardium or the thyroid gland. Carcinogenic and teratogenic effects of cobalt have been observed in experimental systems and/or humans (De Boeck *et al*., 2003). At the moment the main cause of interest of this study, concerning occupational cobalt exposure are hypersensitivity reactions such as allergic contact dermatitis and possible carcinogenesis.

2.5 Dermal exposure

Cobalt is able to penetrate the skin and cause adverse health effects (Larese Filon *et al*., 2009) therefore a discussion will follow on skin histology, skin function and the percutanaous absorption of cobalt.

2.5 1 Histology of the skin

The skin is generally not acknowledged for its marvel architecture and function although it covers the whole body, has a square surface of 1.2 to 2.2 meters, weighs 4 to 5 kilograms and accounts for approximately 7% of the body weight of an average adult. It is also called the integument, which means “covering” and serves a function

well beyond just covering the body. The skin is flexible and tough to withstand the constant punishment given by external agents, thus it has a largely supportive function. The skin thickness varies from 1.5 mm to 4.0 mm or more in different parts of the body (Marieb and Hoehn, 2007).

The skin consists of two separate layers, the epidermis and the dermis. The outermost layer (epidermis) is the most protective defence against external stressors imposed on the body. The underlying dermis, is the largest part of the skin, it is a tough leathery layer mainly composed of fibrous connective tissue. Under the skin layer is subcutaneous tissue called the hypodermis (Marieb and Hoehn, 2007).

The hypodermis is on top of the tough connective tissue of the skeletal muscle. The hypodermis contains a lot of adipose tissue, which also has a cushioning effect against mechanical stressors. This layer anchors the skin to the underlying structures (mainly muscles), though it can slide relatively free over those structures (Marieb and Hoehn, 2007).

Epidermal appendages such as hair follicles, sebaceous glands and eccrine glands span the epidermis and are embedded in the dermis. The dermis is the only layer, which is vascularised. The blood supply (capillaries) to the epidermis originates in the rete ridges at the dermal-epidermal junction. The hair follicles and the secretory cells of the eccrine (sweat) glands are supplied with blood by these capillaries. A salt dilution is carried to the surface of the skin by the ducts of these glands, which will then evaporate and provide cooling (thermoregulation). The interfolicular epidermis mainly consists of keratinocytes, which are firmly attached to each other and to the basement membrane (Cohen and Rice, 2003). The keratinocytes of the basal layer is a continually renewing cell population, representing the youngest part of the keratinocyte population (Marieb and Hoehn, 2007; Cohen and Rice, 2003).

The mitotic nuclei of the basal cell layer undergo rapid division; the progeny detaches from the basal lamina and migrates outward, towards the skin surface. These cells undergo a program of terminal differentiation and new protein markers are gradually expressed and accumulation of keratin proteins occurs. The migrating cells form the outermost layer of the skin, the stratum corneum (SC). The mature cells (called corneocytes) contain about 80% keratin and are no longer viable. The cells are gradually shed on the outermost surface and replaced by basal cells which will mature and eventually shed as well. The basal cells take about two weeks to reach the SC and another two weeks for the cells to be shed from the surface. Biological

protection strategies are also facilitated by the SC, which acts as a biosensor via signalling between the SC, epidermis and deeper skin layers, as well as by the changes of SC permeability in response to humidity changes and perceptions (Elias, 2007).

2.5.2 Percutaneous absorption

The SC is the primary skin barrier, which consists of dead keratinocytes (corneocytes) embedded in a lipid bilayer matrix. The structure is compact and dense, and is often described as a "brick and mortar" structure. The lipid bilayers, "the mortar", control the rate at which a substance is able to penetrate the skin barrier. Common skin-damaging factors such as solvents, excessive hydration and soaps cause adverse health effects by primarily targeting the lipid bilayers (Kezic and Nielsen, 2009).

Skin is not a complete impermeable barrier, but allows the ingress of topical substances. Topically applied substances can follow three possible penetration pathways: 1) intracellular; 2) intercellular and 3) follicular routes (also know as shunt pathway). Poorly permeable substance can be taken up easier if the barrier is compromised by factors such as diseases (e.g. psoriasis) and other conditions (e.g. abrasion, wounds). The viable layer of the epidermis can allow hydrophilic agents to diffuse easily into the intercellular water, and hydrophobic agents can move across the cell membrane, each can diffuse into the blood supply in the rete ridges of the dermis. Water loss through the skin is prevented by the SC (Schaefer, 1996).

Twenty percent of the SC consists of water, therefore it is generally hydrated. Prolonged immersion of corneocytes allows the cell to take up excess water in the skin layer thereby reducing the barrier function against agents with a hydrophilic nature. A common technique to enhance absorption of agents applied to the skin surface is to occlude the skin by wrapping it in plastic, permitting the retention of perspiration underneath the plastic (Cohen and Rice, 2003). Grubauer *et al.* (1989) found in their study, that occluding the skin membrane of damaged skin, delays the replenishing of skin barrier functions. Kezic and Nielsen (2009), reported that hydration/occlusion of the skin is a mechanism which can alter the skin barrier function. Increased skin hydration can occur when skin has been immersed in water for a long period or when evaporation is prevented/decreased for example when wearing a glove or protective clothing (Kezic and Nielsen, 2009).

The lipid content of the intercellular space gives it a hydrophobic character. Sphingolipids are the major lipid components, which has a high content of long-chain ceramides. The removal of sphingolipids seriously compromises the barrier function as measured by transepidermal water loss (TEWL). TEWL is measured to study the water barrier function of human skin and the measurement is expressed in grams per square meter per hour. A good functioning skin barrier has a high water content and a lower TEWL (Mündlein *et al*., 2008). Increases in TEWL is often the consequence of altered integrity of the SC and therefore decreased barrier function. A healthy hydrated SC is flexible but it can become hard and brittle when it is dehydrated (Mündlein *et al*. 2008).

By using the *in vitro* Franz cell system, Larese Filon *et al*. (2004, 2007) showed that cobalt powders dissolved in synthetic sweat can release metallic ions (Co^{2+}), which permeate the skin. Significant amounts of cobalt was found to be present in the skin itself. The steady-state flow of percutaneous cobalt permeation was calculated as 0.0123 ± 0.0054 µg cm^2/h, with a lag time of 1.55 ± 0.71 hours. Cobalt present in the skin can cause an allergic reaction in persons sensitised to cobalt, resulting in subsequent skin manifestations (refer to 2.7.5 for more detail). Higher concentrations may get into the blood stream. Studies also proved that these powders permeate to a greater extent through damaged skin than intact skin (Larese Filon *et al*., 2009).

Many exogenous factors influence the skin permeation rate of transition metals: Some of these factors, as discussed by Hostynek, (2003) will be highlighted: i) Dose; the rate of diffusion of certain transition metals is not proportionate to the applied concentration. ii) Vehicle; the effect of the vehicle for percutaneous absorption is a critical factor when considering the effect the vehicle will have on the permeant solubility and on the skin barrier properties. Larese Filon *et al*. (2004) proved that cobalt powders dispersed in synthetic sweat are able to permeate the skin opposed to cobalt powders alone. iii) Molecular volume; there is a significant correlation between the diffusitivity through skin and the size of a metal species, the counter ions are also a determining variable. iv) Valence; the ion's electrophilicity and protein reactivity changes with the number of outer electrons (change in ionic radii). v) Solubility and pH dependence; the penetration of electrolytes are affected by changes in pH.

Some endogenous factors that influence percutaneous absorption, as discussed by Hostynek 2003 will be highlighted: 1) Age of the skin; it is known that children have

more incomplete barrier functions. Skin function deteriorates with age, which leads to development of various benign and malignant diseases. 2) Anatomical site; metals have been observed to have the following decrease in rank order of permeability: scrotum-forehead-abdomen-forearm-leg–back (Wester en Maibach, 1980). 3) Oxidation and reduction of xenobiotics in the skin; reduction may lead to a discoloration of the skin due to the element in the metatallic state and oxidation may lead to a higher immunogenecity of certain metals (Hostynek, 2003).

2.6 Respiratory exposure

Particles deposited in the respiratory tract have the potential to cause or exacerbate lung diseases, including asthma, bronchitis and chronic obstructive pulmonary disease. Not only can inhalation of particles have numerous pathological effects on the respiratory tract, it can also cause cancer and affect other organ systems such as the cardiovascular system and nervous system (Bonner, 2007). The most important occupational route of exposure to particulates is through inhalation of airborne substances. Cobalt sulfate is a powdery substance, which can easily become airborne and deposited in the respiratory tract by inhalation. The respiratory tract will be discussed to better understand occupational exposure to particulates.

2.6.1 The respiratory tract

The respiratory tract can be divided into two systems, the upper- and lower airway passages. The upper airway passage begins at the nose, nasal passages, mouth and the pharynx down to the vocal cords in the larynx. The lower airway passage begins at vocal cords, extends down the trachea to the alveoli in every bronchial tree. The bronchial tree consists of more passages branching off from the trachea to form two primary bronchi, which enter the lungs. The primary bronchi branches into more secondary bronchi as it enters the lungs. Air is conducted to and from the bronchial segments by tertiary bronchi, which branch of the secondary bronchi. There are ten bronchial segments in the right lung and eight in the left lung (Lamprecht, 2007).

At the end of the bronchioles are tiny air sacks, which are called alveoli where the most important function of the lungs occurs namely, gas exchange (CCOHS, 1999). There are an estimate of 300 million alveoli in two adults lungs and covers a surface area of 160 m^2. The large surface area maximises the gas exchange area between O_2 and CO_2 (Wiebel, 2009).

2.6.2 Particle deposition in the respiratory tract

The number of particles inhaled and deposited in the respiratory tract depends on: 1) the size, shape, and density of the particulate, 2) the amount of contaminated air inhaled, 3) the geometry of the respiratory tract, which can differ for each person (Radiation Sources, 2009). Deposition of particles mainly occurs through the following mechanisms (Witschi and Last, 2003):

a) Interception. Interception in the respiratory tract occurs when the edge of the particle is close enough to the surface that the particle contacts the airway wall. This method of deposition is important for elongated particles such as fibres. As the airway diameter decreases, the chance for interception of a particle increases (Radiation Sources, 2009).

b) Impaction. Particles suspended in air tend to travel along the air stream it is carried by. When the particle's momentum is too high to change direction with the air stream, impaction occurs for example at an airway bifurcation. An increase in particle size, particle density, and air velocity will enhance the chance of impaction (Witschi and Last, 2003).

c) Sedimentation. Deposition caused by the downward force of gravity working against the upward force of air in the respiratory tract causing a particle to be forced in a downward direction. An increase in the particle size, particle density, and length of time spent in the airway increases the chance of sedimentation (Witschi and Last, 2003).

d) Brownian Diffusion. This is an important deposition mechanism for sub micrometer particles. The impact of gas molecules impart random movement on particles. This movement can result, in the particle contacting the airway wall. Brownian diffusion occurs mostly in areas of the airway where bulk flow is low or absent such as the bronchioles and alveoli (Radiation Sources, 2009).

The behaviour of particles in the respiratory tract is well understood and can be used to estimate the region in which a particle will be depositioned (Heyder, 2004). The position of particle deposition after inhalation in the respiratory tract is greatly determined by the aerodynamic diameter (AD) and shape of the inhaled particle. The sizes of particles able to enter the respiratory system have been divided into three groups according to the area it may be deposited. Inhalable particles can enter the nose and mouth during breathing and have an AD of up to 100 μm. Thoracic particles

can enter the lung airways if the particle has an AD of less than 30 µm. Respirable particles are so small that they are able to locate in the lungs sacks and bronchioles if the have an AD of 10 µm (Belle and Stanton, 2007).

Debates between different organisation regarding what size should be classified as respirable are ongoing. Opinions about the practicability of the monitoring of different size substances and the effects, which small particulates may have in an occupational setting, are amongst the main topics of discussion. When monitoring exposure to airborne particulate it is important to know the estimated size of the particulate as well as in which area of the lung it may have a hazardous effect. Exposure to coarse (large AD) cobalt, which deposits in the nose and mouth, may be easily removed by expectoration and will not have such a hazardous effect as fine cobalt, which may be deposited in the lower airway passages where clearance takes longer (Belle and Stanton, 2007; Zhang *et al*., 2000).

If a particle is hazardous in any part of the respiratory tract sampling should be done using an inhalable sampler with a 50% cut point of 100 µm i.e. has a 50% percent efficiency of collecting all particles with an AD of 100 µm. Thoracic particles are collected for those particles which may be hazardous if deposited anywhere in the lung airways and gas exchange region, the sampling media must be able to have a 50% cut-point of 10 µm. Hazardous respirable particles should be collected if they are hazardous when deposited in the gas exchange region, collection with 50% cut point of 4 µm (Belle and Stanton, 2007).

2.6.3 Clearance of particles

The number of particles, position of particle deposition, and the effects particles have in the respiratory tract and other body systems are determined by numerous factors. The respiratory tract is specialised in protecting the system by employing different lines of defence depending on the nature of the invasion. Respiratory lining tract fluids (RLTFs) are present on the underlying respiratory tract epithelial cells (RTECs) to act as a first line of defence against inhaled toxic gases such as SO_2, O_3, NO_2 and tobacco smoke. The RTFLs may detoxify the pollutants to protect the RTECs (Cross *et al*., 1994).

The outer lining of the respiratory system contains different barrier components, which protect the respiratory system from invading foreign material reaching the lungs and immuno-competent cells. The main components are the surfactant film, mucociliary system, active phagocytic airway macrophages and the tight junctions of

the epithelium. Not all large particles that reach the airways are sufficiently removed by mucociliary action. The physical chemical characteristics and the nature of their interaction with surfactant film at the air-liquid interface greatly determines if it may be cleared or not (Rothen-Rutishauser *et al*., 1995). The clearance of particles in the lungs is a very important defence mechanism.

The faster particles are cleared from the respiratory tract the less time is available to cause damage to pulmonary tissues or permit local absorption. Particles may be cleared to 1) the gastrointestinal tract, 2) the lymph nodes and lymphatics, where it can be dissolved and taken up in the venous circulation, or 3) the pulmonary vasculature. Particles can be deposited in three different distinguished areas of the respiratory tract where they have to be cleared to avoid adverse health effects. Different clearance mechanisms are present in each different area:

1) Nasal clearance. The mucus lined nasal area serves as an initial filtering system when air enters the respiratory tract through the nasal and oral area. Particles, which adhere in the anterior region of the nose, are mainly cleared by extrinsic actions such as wiping or blowing. The mucocilliary epithelium covers the larger parts of the nose where it able to propel mucus towards the glottis after which it can be swallowed and digested. Nasal epithelia are also able to metabolise some foreign compounds (Witschi and Last, 2003; Radiation Sources, 2009).

2) Tracheobronchial clearance. The trachea and bronchi are lined with a layer of mucus, which is able to trap pollutants and debris. The cilia in the respiratory tract drive (mucociliary escalator) particles, which are trapped in the mucus towards the trachea where it can be removed by swallowing or expectoration (Radiation Sources, 2009).

3) Pulmonary clearance. Particles trapped in the lower respiratory tract are removed by several primary ways of which the mucociliary escalator is also an important mechanism as described in the upper airway passages. Particles trapped in the fluid layer of the conducting airways by impaction can be cleared upward by the mucociliary escalator to the tracheobronchial tree to be removed by swallowing or expectoration. Macrophages can phagocytise particles, which will then be cleared by the mucociliary escalator. Alveolar macrophages phagocytise particles, which are removed by lymphatic drainage. Epithelial membranes may be directly penetrated by small particles (Witschi and Last, 2003).

2.7 Health effects of Cobalt

2.7.1 Cobalt an essential element

It was discovered in 1948 that Vitamin B_{12} contains 4% cobalt. The body cannot synthesise cobalt, thus it needs to be absorbed from the diet, as an essential element. Cobalt is easily absorbed from the small intestine. Most of cobalt is excreted via the urine while very little is being retained by the liver and kidneys. The only known function of cobalt in the human body is the integral part it form in Vitamin B_{12}. Instances of cobalt deficiency has never been reported however signs and symptoms of Vitamin B_{12} deficiency has been reported (Baker *et al*., 2003).

2.7.2 Respiratory effects

It has been shown in other studies that occupational exposure to cobalt and compounds of cobalt can cause lung inflammation, fibrosis, emphysema, and alveolar proteienosis (Hartung *et al*., 1982; Moulin *et al*., 1993). The solubility of inhaled cobalt-containing particles in biological fluids and in macrophages determines the absorption rate (IARC, 2006).

Animal studies by Zhang *et al*. (2000) assessed the pulmonary responses to standard cobalt (Std-Co) and ultra fine (Uf-Co) cobalt. Results of their study indicated that Uf-Co is much more toxic to the lower respiratory tract than the Std-Co when the same dose was administered. Instillation of Uf-Co suggests that the Uf-Co firstly damages the epithelia, which results in a lactate dehydrogenase release and protein accumulation resulting from increased epithelium permeability. The increased permeability may allow interstitial access of particles, followed by acute interstitial and alveolar inflammation. Failure to clear the unsaturated particles may lead to persistent inflammation. Activated macrophages increase in number, in response to particle deposition in the pulmonary tract. The release of chemotactic factors attracts polymorphonuclear leukocytes and monocytes follow after the activation. Neutrophils play an important role in defence to microbial infection and are also activated. Activated neurophils and macrophages can release different cytokines, toxic oxygen metabolites and proteienases that can damage the lung parenchema together with stimulating fibroblast proliferation (Martin *et al*., 1987).

Ultra-fine particles constitute a massive number of particles, which may stimulate macrophages to release mediators in exaggerated amounts. The large amount of ultra fine particles may overpower the capacity of the macrophages to phagocytise, which allows particle interaction with the epithelial cells leading to epithelial injury.

The mechanism by which Uf-Co causes a higher pulmonary toxicity was not explained by this study, however the effect of cobalt's diameter was evident. The Uf-Co has a greater surface area than Std-Co, which may explain the fact that Uf-Co caused more pulmonary damage. Particle size is important when considering the effects of particle induced lung disease after deposition in the lungs. This study concludes that Uf-Co is much more toxic to the lungs than Std-Co. The occupational exposure limit for cobalt is solely based on mass and does not take the toxic effects of different particle sizes into account. This fact may have great implication for occupational hygiene regulations (Zhang, *et al*., 2000).

2.7.3 Carcinogenicity

Cobalt sulfate and other soluble cobalt (II) salts have been classified by the IARC as a possible (group 2B) carcinogen. Cobalt metal with tungsten carbide has been classified as a probable (group 2A) carcinogen (IARC, 2006). Several reports investigated by the IARC (2006) provide evidence of an increased lung cancer risk in France, related to exposure to hard-metal dust containing cobalt and tungsten carbide. Un-sintered hard-metal dust appears to pose a higher risk than sintered hard-metal dust. Risk of developing lung cancer increases, with increased duration of exposure. Potential confounding by smoking and other occupational carcinogens were taken into account. A study in Sweden where workers were exposed to cobalt and tungsten carbide showed increased mortality from lung cancer. Hard-metal factories in France where workers were exposed to cobalt in the absence of tungsten carbide showed that the risk of developing lung cancer increased two fold (IARC, 2006).

Valko *et al*. (2005) reported that many experimental studies show that cobalt can not only interfere with DNA repair processes but also cause direct induction of DNA damage, DNA-protein cross linking, and sister-chromatid exchange. The mechanism by which cobalt induces cancerous and toxic effects are not well understood, it has been established that cobalt mediates free radical generation that contributes to cobalt carcinogenicity and toxicity. Many different mechanisms by which cobalt may possibly interact with free radicals have been identified (Valko *et al*., 2005).

2.7.4 Neurotoxicity

Research experiments conducted by Persson *et al*. (2003) showed that cobalt might be a neurotoxic metal when absorbed through the nasal mucosa. The olfactory epithelium in the nasal cavity is in constant contact with the environment. It acts as the primary olfactory neurons. The olfactory epithelium serves as a link to the

olfactory bulb in the brain, which may also serve as a pathway where substances can be carried to the brain. Intranasal administration of $_{57}Co^{2+}$ in rats showed that the metal was taken up in the olfactory mucosa and transported to the olfactory bulbs of the brain. The olfactory nerve layer and the terminals of the primary olfactory neurons in the glomular layer of the bulbs were the areas in which metal tended to accumulate. Cobalt was also able to travel deeper into the olfactory cortex as was evident by the presence of cobalt in the interior of the bulbs and the anterior parts of the olfactory cortex. Many workers exposed to hard metals have reported memory deficits. It is important to consider metal neurotoxicity by absorption through the nasal cavity when compiling risk assessments and management of the health risk.

2.7.5 Allergic Contact Dermatitis

Drugs and chemicals applied to the skin can result in local reactions in response to the applied compound or its formulation. Cobalt is a known sensitiser and can increase contact allergic contact dermatitis (ACD) in sensitised persons (Larese Filon *et al.,* 2004; Julander *et al.,* 2009). Cross reactions with nickel as well as co-sensitisation is a frequent occurrence (Shirakawa *et al*., 1990). Reactions may range from general reactions as characterised by an adaptive immune or allergic response to a specific reaction, to a localised alteration of the SC. Two phases note the progression of ACD: (1) a sensitization phase when the host is immunised to the allergen, and (2) the elicitation phase, characterised by a rapid secondary immune response after re-exposure to the allergen. ACD manifests in the elicitation phase (Alenius *et al*., 2008).

Contact allergens are typically small and reactive molecules with irritant properties. It penetrates the upper layer of the skin and interacts with skin proteins to form hapten-carrier protein complexes after which a cascade of immune reactions continue to sensitise the individual. Re-encountering of the same hapten by a previously sensitised individual can result in an elicitation phase that manifests as ACD. A day or two after the onset (delayed type hypersensitivity) of the elicitation phase clinical signs of heat, itching, oedema and vesicles are caused by leukocyte infiltration in the skin (Sallusto *et al*., 2000).

2.8 Occupational exposure

In most occupational settings there are more then one chemical being used, which workers are exposed to. Mostly chemical exposures are monitored individually and it is assumed that the different chemicals have an additive effect on the health of the worker. The possibility that more than one chemical can perhaps have a synergistic

effect which has not yet been taken into account so often. The traditional assumption has been that if individual chemicals have equivalent health end points, a mixture of these similar chemicals will have mutually independent effects and the toxic response to several chemicals is additive (Cross *et al*., 2001).

Nickel and cobalt are two metals, which are usually present together in occupational settings such as mines, smelters, and refineries (Cross *et al*., 2001). Nickel ore processing yields cobalt as a by-product and cobalt alloys often include nickel (Lauwerys and Lison, 1994). Thus simultaneous occupational exposure to different concentrations of these metals is often occurring.

The adverse health effects of cobalt and nickel have been studied individually, but only a few studies focused on their combined effect. It is suggested by Johansson *et al*. (1991) that exposure to nickel and cobalt chloride mixtures have a synergistic effect on certain aspects of the pulmonary morphology. Data from previous studies by Johansson *et al*. (1989) showed that combination of $NiCl_2$ and $CoCl_2$ induced a synergistic response in the respiratory tract, as signified by the type II cell aggregates and concentrations of phopholipids. Alveolar type II cells are likely to be damaged when humans inhale $NiCl_2$ and $CoCl_2$. Findings from Cross *et al*. (2001) that mixtures of $NiCl_2$ and $CoCl_2$ induces a synergistic toxic response in cell cultures are consistent with that of Johansson *et al*. (1991) *in vivo.*

Traditionally the respiratory exposure route has been seen as the most important pathway. Many cobalt respiratory exposure studies have been done, which reported increased risk of developing cancer due to cobalt exposure (Lasfargues *et al*., 1992; Moulin *et al*., 1998; Tüchsen *et al.,* 1996). Kusaka *et al*. (1986) reported very high concentrations ranging from 7 to 6390 mg/m^3 in the cobalt powder preparation area of hard metal industries. Exposure to cobalt is highly variable depending on the type of exposure. Assessment of different types of industries and process will assist in identifying and managing the possible health risks.

Cobalt skin exposure in different occupations has been assessed by a few authors (Larese Filon *et al*., 2004, Liden *et al*., 2008, Julander *et al*., 2009), but none have done a study in a base metal refinery. Liden *et al*. (2008) studied exposure of nickel, chromium and cobalt of workers who come into contact with metallic items. Julander *et al*. (2009) found that low concentrations of cobalt are able to elicit allergic contact dermatitis in sensitized persons. Little information and research exists concerning the dermal exposure to cobalt, especially in base metal refineries.

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- Units and symbols: SI units should be used, though their equivalent in other systems may be given as well.
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  Vincent JH. (1989) Aerosol sampling: science and practice. Chichester, UK: John Wiley. ISBN 0 471 92175 0.

CHAPTER 3

Dermal and respiratory exposure to cobalt salts in a packaging area of a base metal refinery

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ABSTRACT

Objectives: The objectives of this study were to assess dermal and respiratory exposure of workers at a cobalt packaging area of a South-African base metal refinery and to assess their skin condition by measuring transepidermal water loss (TEWL) and skin hydration indices.

Methods: The skin hydration index was measured on the palm, back of the hand, wrist and forehead before shift, during and end of shift. The TEWL index was measured at the start and end of shift on the same areas as the hydration indices. Ghostwipes™ were chosen as preferred wipe sampling media to collect dermal and surface exposure wipe samples. Wipe surface samples were collected from suspected contaminated surfaces in the packaging area. Respiratory samples were taken by using the Institute of Occupational Medicine (IOM) inhalable aerosol sampler at a flow rate of 2 l/min. Wipes and respiratory samples were analysed for cobalt according to NIOSH method 9102, using an ICP-AES**.**

Results: The hydration indices indicated that workers skin are slightly dry to normal. Hydration on the wrist increased significantly during the shift. TEWL indices increased significantly on the back of the hand, wrist and forehead during the shift. TEWL indices of the palm showed a low barrier function before the shift which deteriorated further to a very low barrier function at the end of the shift. Significant dermal cobalt loading occurred on the back of the hand, wrist and palm during the shift. The palm was most exposed and the forehead the least. Workplace surfaces were contaminated with cobalt. Respiratory exposure exceeded the occupational exposure limit for most of the workers. STEL exposures exceeded the limits for half of the workers.

Conclusion: The barrier function decreased from strained to critical during the shift probably due to the high levels of dermal cobalt exposure. Respirable exposure exceeded the OEL. Workers are at risk of developing the adverse health affects associated with cobalt. Exposure levels measured are the result of engineering process failures and inadequate management and use of PPE.

INTRODUCTION

Cobalt sulfate has a range of industrial and agricultural uses. Cobalt and its compounds are classified as a possible (group 2B) human carcinogen (IARC, 2006) and is a known sensitiser causing allergic contact dermatitis (Kezic and Nielsen, 2009; Julander *et al.,* 2009). Exposure to metals can occur through different exposure routes. Potential respiratory toxicity of substances has traditionally been prioritised over other exposure routes such as dermal exposure (Cherrie *et al*., 2006). Many cobalt respiratory exposure studies have been done, which reported increased risk of developing cancer due to cobalt exposure (Lasfargues *et al*., 1992; Moulin *et al*., 1998; Tüchsen *et al.,* 1996).

Transepidermal water loss (TEWL) indicates the integrity of the skin barrier function (Verdie-Sévrain and Bonté, 2007). A good barrier function protects the integument system from absorbing potentially harmful substances into the body where it can act locally or systemically (Alenius *et al*., 2008). *In vitro* studies also proved that cobalt powders permeate to a greater extent through damaged skin than intact skin (Larese Filon *et al*., 2009).

Subjective opinion about skin condition can differ remarkably with the actual skin condition (Du Plessis *et al*., 2010). Persons are often under the impression that they have a healthy skin, while hydration levels and TEWL measurements indicate the opposite. Some individuals are more susceptible for local as well as systemic toxicity to exposure of a chemical due to inherent poor skin condition (Kezic and Nielsen, 2009).

Cobalt is a water soluble salt, which can not be absorbed through the skin in its pure form unless it is in an ionic form. By using the *in vitro* Franz cell system, Larese Filon *et al*. (2004, 2007) showed that cobalt powders dissolved in synthetic sweat can release metallic ions, which permeate the skin. Kezic and Nielsen (2009) reported that hydration/occlusion of the skin is a mechanism which can alter the skin barrier function. Increased skin hydration can occur when skin has been immersed in water for a long period or when evaporation is prevented/decreased for example when wearing a glove or protective clothing (Kezic and Nielsen, 2009).

According to the Mine Health and Safety Act, 1996 (Act no. 29 of 1996) of South Africa, Occupational Hygiene Regulation, the 8 hour occupational exposure limit (TWA-OEL) for cobalt and cobalt-compounds is 0.05 mg/m^3 with no skin notation.

Cobalt skin exposure in different occupations has been assessed by a few authors (Larese Filon *et al*., 2004, Liden *et al*., 2008, Julander *et al*., 2009), but none have done a study at a base metal refinery. A lack of information and research exists concerning the dermal exposure to cobalt, thus further studies related to dermal exposure are important to assess the risk related to dermal cobalt exposure. The aims of this study were to assess dermal and respiratory exposure of workers at a cobalt packaging area of a South-African base metal refinery and to assess their skin condition by measuring TEWL and skin hydration indices.

METHODOLOGY

Study design and sampling strategy

In an availability study at a base metal refinery potential respiratory and dermal exposure to cobalt-sulfate were assessed concurrently in the $CoSO_4$ packaging area. Four workers participated on each sampling day (total of three days).

Description of workplace and work method

The packaging area is located at a base metal refinery. Figure 1 depicts a simplified workflow of the cobalt packaging area, which entails the packaging of cobalt from bulk bags into sealed 25 kg bags. One worker is stationed at each of the different mentioned sections.

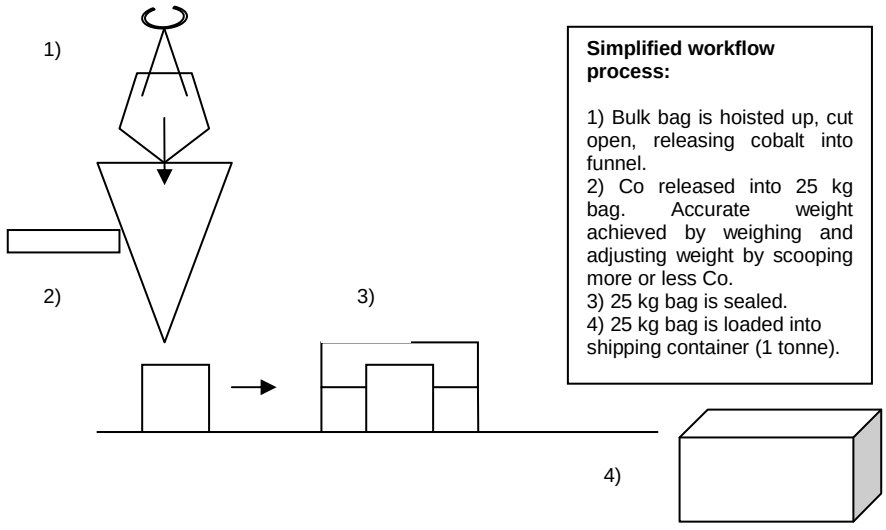

Figure 1: Simplified workflow of the cobalt packaging process

Respiratory exposure

The objective was to explore the relation between personal airborne dust exposure and skin exposure, therefore dermal and personal sampling was done concurrently**.** Personal airborne dust sampling of cobalt was conducted by using the Institute of

Occupational Medicine (IOM) inhalable aerosol sampler, 0.8-µm cellulose ester membrane filters and cellulose backup pads. The Apex Pro sampling pumps (Casella ®, United Kingdom), were calibrated at a flow rate of 2.0 l/min before and after use. The sampling head was attached in the breathing zone of each worker for the whole duration of the shift to assess the 8 hour exposure. For STEL samples, 4 random sampling times of 15 minutes each were selected during the 8 hour shift. Samples were analysed by an accredited laboratory using NIOSH method 9102.

Dermal Sampling

Dermal exposure to cobalt was assessed by making use of a removal method by wiping the skin contaminant layer with a commercially available skin wipe, Ghostwipe ™ (Environmental Express, Mount Pleasant, S.C). Each wipe is an individually packaged (15-cm x 15-cm) non-woven fabric sheet and is pre-moistened with deionised water. Pre-moistened and packaged wipes allows for greater consistency of the moisture content, when compared to methods such as acid wipe sampling used by Liden *et al*. (2008), which have to be individually moistened before taking the sample. The Ghost Wipe ™ is also ideal for analysis as it dissolves completely during the digestion procedure of the analysis so that the whole sample can be used.

Templates made of acetate paper with a rectangular aperture of 10 cm^2 were used to maintain a uniform and controlled area to attain a wipe sample. A clean template was used for each sample. The template was placed on the desired sampling area and held in place by the researcher with one hand while using the other hand to wipe the skin. The area was wiped four consecutive times in alternating horizontal directions. Before alternating the direction of the wipe, it was folded in half. A clean pair of vinyl rubber gloves were worn for each wipe sample taken. Each day of sampling, three field blanks were also included for analysis. Samples were analysed by an accredited laboratory using NIOSH method 9102.

The anatomical areas most likely to be exposed were included, which are the palms, back of the hand, wrist and forehead. Sampling was done at the following intervals: 1) before shift, 2) during (prior to tea break) and 3) end of shift. A total of 12 samples per worker per day were collected.

Observations

Non-routine tasks, which can result in unusually high or low exposure, shift duration, unhygienic habits, and high or low production rates were noted.

Validation study

The Occupational Safety and Health Administration's Method ID125G reported on the efficiency of Ghostwipes™ as a sampling media to remove metals from surfaces. The analytical recovery of samples spiked with cobalt liquid dilution was reported as 98.2%. The removal efficiency from a glass surface with cobalt was reported as >90% efficient. The reproducibility of the sampling method between different persons were between 86.6 and 95.2% (OSHA, 2002).

Skin condition

Hydration and TEWL indices of the skin were measured using a Dermal Measurement Unit, EDS 12 (Enviroderm, UK). Two measurements were made on each dermal wipe sampling area, namely; palm, back of the hand, wrist and forehead. The hydration indices were measured at all three sampling intervals. TEWL indices were measured before the shift and at the end of the shift.

Table 1: Range and interpretation of hydration index measurements

Hydration Index	Skin condition
1	Extremely dry
2	Very dry
3	Dry
4	Slightly dry
5–8	Normal
9–12	Excessively hydrated

Table 2: Range and interpretation of TEWL index measurements.

TEWL index	Skin barrier function	Skin condition
0–4	Excellent	Very healthy
5–9	Good	Healthy
10–12	Normal	Normal
13–16	Low	Strained
17–20	Very low	Critical

Surface sampling

Surface areas in the packaging area where workers may be exposed to cobalt were sampled. Five surface wipe sample were taken per sampling day. A S-shaped wipe pattern was used to wipe the 100cm² aperture area of the template. The area was wiped four consecutive times in alternating horizontal and vertical directions.

The following items in the packaging area were sampled for each sampling day:
3 x 25 kg packaged cobalt bags (just before being sealed in the shipping container),
1 x 1 tonne bulk bag and 1 x face of the scale.

Skin questionnaire

Dalgard *et al*. (2003) composed a self-reported skin questionnaire to quantify the absence or presence of skin disease in the community. A validation study was included and it was found to be a useful tool to quantify and explore skin diseases at population level. This questionnaire consists of ten basic questions. The first question 'Do you have itchy skin?' is purely subjective while all the others are objectively associated with visual signs. The mean of the ten questions will reflect the self-reported score. The questionnaire has been translated in Setswana, since the majority of workers are Setswana speaking.

Statistical Method

Statistical analysis was done, by using SAS JMP® 8.0 software. Statistical analysis included basic statistics (mean, standard deviation, variations). A goodness of fit test (Shapiro Wilk-W test) was applied to determine the normality of the data. One-way analysis of variance (ANOVA) repeated measures was applied to analyse significant differences within groups. Tuckey-Kramer post test to determine least significant difference between pairs within groups was also done. Dermal and respiratory results which were under the detection limit were divided by two.

RESULTS

All workers who work in the cobalt packaging area participated in this study. Each worker wore a standard two piece overall, Injati gloves (Pienaar Bros (Pty) Ltd, South Africa), safety glasses, hard hat and a dust mask (3M FFP2). Personal protective equipment (PPE) was taken off randomly during the shift, especially gloves and dust masks.

The hydration indices (arbitrary units) as shown in fig. 2 for the palm increased from 2.041 ± 0.284 to 3.500 ± 0.781 during the break, to 3.291 ± 1.342 at the end of shift. The hydration indices for the back of the hand increased from 3.583 ± 0.701 to 4.375 ± 0.712 during the break, to 4.166 ± 0.360 at the end of shift. The hydration indices for the wrist increased from 4.375 ± 0.083 to 5.291 ± 0.975 during the break to 6.041 ± 0.369 at the end of shift.

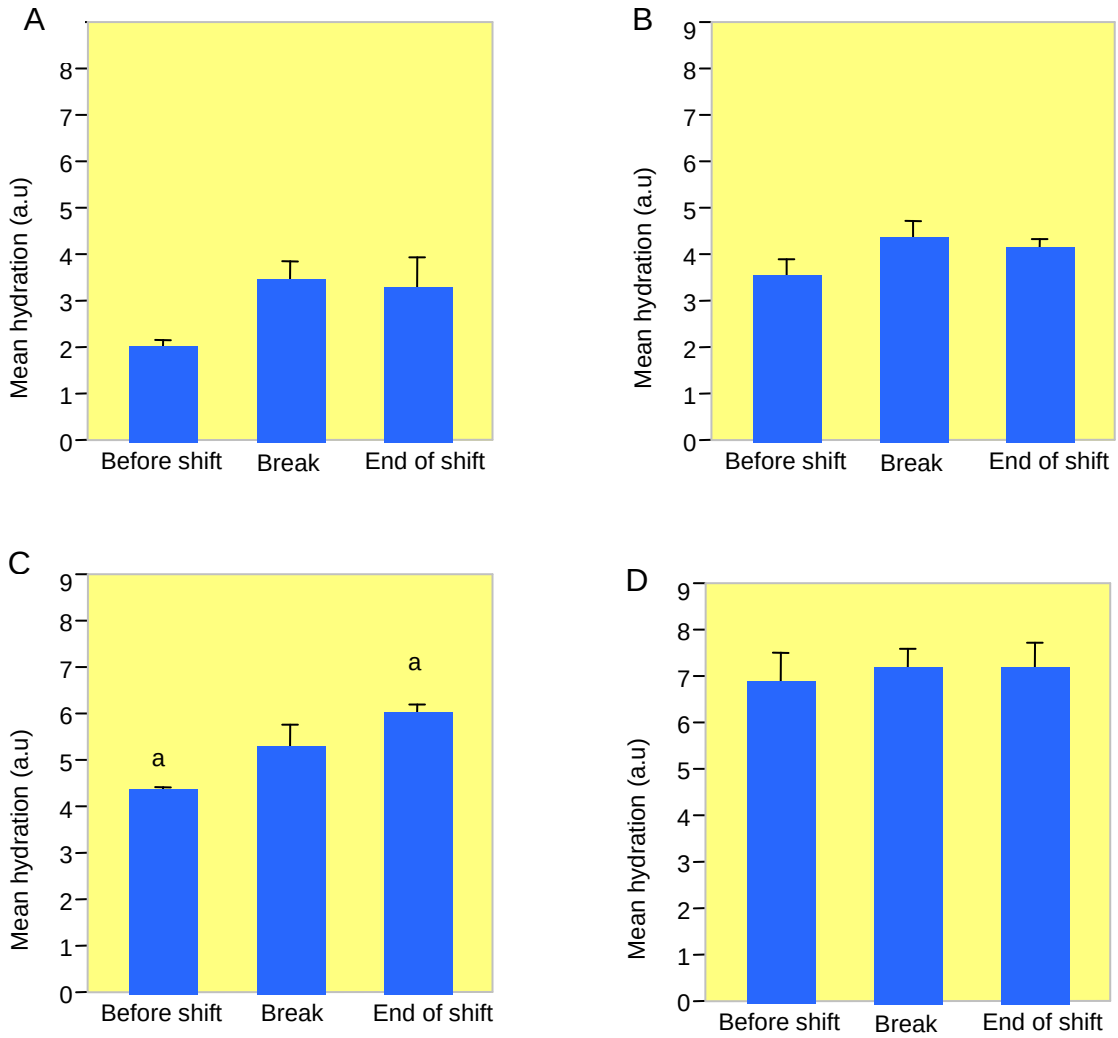

Figure. 2 Hydration index for (A) palm, (B) back of hand, (C) wrist and (D) forehead. Statistical significance as determined by repeated measures ANOVA is indicated by a. (a.u = arbitrary units.)

The repeated measures ANOVA showed that the wrist is the only anatomical site, which had a statistical significant increase of hydration indices during the shift ($p=0.0091$). The repeated measures ANOVA showed that the hydration indices on the forehead of all workers are inconsistent before the shift, during and at the end of the shift. The inconsistent hydration indices on the forehead do not indicate a decrease or increase for the group of workers during the shift. The statistical difference for hydration indices on the wrist of workers within the group is $p=0.0028$.

Table 3. TEWL index for the palm, back of hand, wrist and forehead and repeated measures ANOVA test.

		TEWL index (arbitrary units)				
		Mean	**SD**	**Minimum**	**Maximum**	**P-Value**
Palm	Before shift	14.958	2.374	12.333	17.500	0.096
	End of shift	17.875	0.975	16.667	18.667	
Back of hand	Before shift	9.958	1.802	8.333	12.500	**0.049**
	End of shift	13.667	1.986	10.833	15.333	
Wrist	Before shift	9.583	1.635	7.500	11.500	**0.002**
	End of shift	16.416	1.174	15.167	18.000	
Forehead	Before shift	11.958	0.598	11.500	12.833	**0.048**
	End of shift	14.667	2.215	12.667	17.833	

Repeated measures ANOVA showed that there is a statistical significant increase between the mean TEWL index before the shift and the end of the shift on the back of hand (p=0.0486), wrist (p=0.002), and forehead (p=0.0484). It is clear that transepidermal water loss increased from before the shift towards the end of the shift in these areas. The mean TEWL index on the palm did not show a statistical significant difference between before and the end of the shift, although the palm recorded the highest mean (low barrier function) compared to the other anatomical areas.

The self-reported skin complaints were: 100% troublesome sweating, and 25% scaly skin. The severity of the troublesome sweating and scaly skin complaints reflected are trivial (not justifying medical attention) according to the Dalgard *et al*. (2003) skin questionnaire's scoring system. No complaints were reported regarding, itchy skin, dry/sore rash, itchy rash on the hands, pimples, rash on face, warts, loss of hair or other skin problems.

Table 4. Cobalt deposited on the skin

		Co (µg/cm^2)			
		GM	**GSD**	**Minimum**	**Maximum**
Palm	Before shift	2.640[a]	1.571	1.431	6.363
	Break	19.815	1.912	11.221	40.213
	End of shift	23.070[a]	3.892	6.363	104.248
Back of hand	Before shift	0.599[b]	2.013	0.491	2.16
	Break	10.446	2.012	5.986	29.081
	End of shift	7.106[b]	3.122	1.735	26.671
Wrist	Before shift	0.830	1.986	0.610	3.167
	Break	13.928	3.880	4.192	84.203
	End of shift	11.565	4.645	2.198	71.885
Forehead	Before shift	0.413[c]	1.328	0.236	3.033
	Break	6.332	1.750	3.339	9.773
	End of shift	2.978[c]	1.688	1.682	5.889

GM, geometrical mean. GSD, geometrical standard deviation. a, b and c indicates statistical significant differences between means by repeated measures ANOVA.

Dermal exposure data are presented in Table 4. Detectable levels of cobalt were present on the palm, back of hand, wrist and forehead before the shift commenced. The forehead was the least exposed, cobalt levels ranged from 0.413 ± 1.328 µg/cm^2 and 2.978 ± 1.668 µg/cm^2. Loading of cobalt onto the palm of the hand was highly variable ranging from 2.64 ± 1.571 µg/cm^2 to 23.070 ± 3.892 µg/cm^2. The geometric mean cobalt loading on the palms was the highest amongst the different areas before and after the shift.

The amount of cobalt deposited on the skin was statistically different between before and the end of the shift for the palm (p=0.0280), back of hand (p=0.0399) and forehead (p=0.0157). Loading of cobalt on the skin did significantly increase from the beginning of the shift towards the end of the shift. The geometric mean of cobalt skin loading on the back of hand, wrist and forehead decreased after the break. The palm is the only area where cobalt loading was higher at the end of the shift compared to the break.

Table 5. Dermal cobalt exposure: Pair-wise correlation between anatomical areas.

Dermal cobalt exposure: pair-wise correlation between anatomical areas			
Area 1	**Area 2**	**R-Value**	**P-Value**
Palm	Back of hand	0.928	0.072
Palm	Forehead	-0.936	0.064
Wrist	Back of hand	**0.999**	**0.001**
Wrist	Forehead	-0.884	0.116
Wrist	Palm	0.923	0.077
Forehead	Back of hand	-0.882	0.118

A pair-wise correlation was done to assess if there are significant correlations between different dermal exposure areas. In order to calculate the mean total dermal exposure of each area for the correlations, the mean exposure at the break was added to the mean exposure at the end of shift. The wrist and back of the hand were the only areas which showed a significant correlation of p=0.001 and r=0.999. The palm and back of the hand (p=0.072, r=0.928), and the wrist and palm (p=0.077, r=0.923) are leaning toward a statistically significant correlation.

Surfaces in the packaging area, which workers had to touch during the packaging process, had detectable levels of cobalt on the surface.

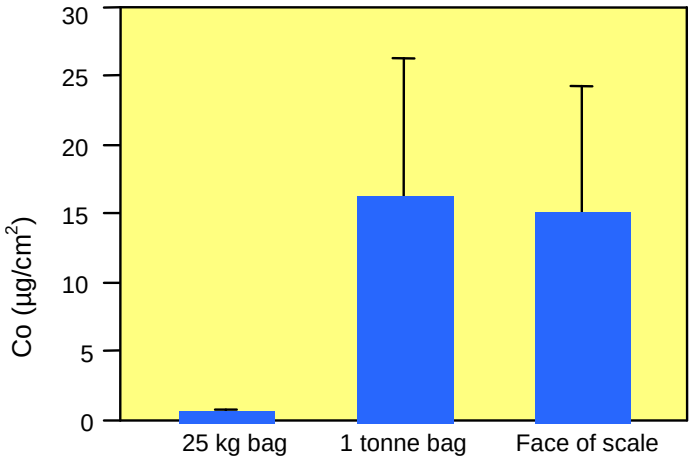

Figure 3. Cobalt surface contamination (µg/cm^2)

The cobalt is supplied in a 1 tonne bag which had detectable levels of cobalt ranging from 1.484 µg/cm^2 to 35.425 µg/cm^2 (n = 3). The face of the scale was touched when manually checking each 25 kg bag's weight. The cobalt levels ranged from 1.1858 µg/cm^2 to 32.335 µg/cm^2 (n = 3). The mean surface contamination on the

exterior of the 25 kg bags is 0.749 µg/cm^2 (n = 12), ranging between 0.181µg/cm^2 and 1.238 µg/cm^2.

Table 6: Mean surface contamination

	Surface cobalt contamination (µg/cm^2)			
	Mean	**SD**	**Min**	**Max**
25 kg bag	0.749	0.351	0.181	1.238
1 tonne bag	16.341	14.175	1.484	35.425
Face of scale	15.243	12.896	1.1858	32.335

Table 7. TWA and STEL respiratory cobalt exposure of individual workers on each sampling day.

	Cobalt respiratory exposure							
	TWA-mg/m^3				**STEL mg/m^3**			
	Day 1	**Day 2**	**Day 3**	**Mean**	**Day 1**	**Day 2**	**Day 3**	**Mean**
Worker 1	**0.036**	**1.358**	**0.032**	**0.475**	0.039	0.029	**1.554**	**0.541**
Worker 2	**0.108**	**0.133**	**0.490**	**0.244**	0.065	0.074	0.135	0.091
Worker 3	**0.392**	**0.052**	**0.430**	**0.291**	0.003	0.038	**1.590**	**0.544**
Worker 4	0.001	0.006	0.012	0.006	0.001	**0.403**	0.027	0.143

No OEL-STEL has been specified for cobalt and compound of cobalt under the Mine Health and Safety Act. As guidance when controlling short-term excursions in exposure, the concentration of three times the OEL-TWA is used (Belle and Stanton, 2007).

All the TWA and STEL respiratory cobalt exposures of worker 4 are below the acceptable limits, except for one STEL exposure of 0.403 mg/m^3. Worker 4 is situated the furthest from the airborne cobalt sources. It is questionable whether this result is representative of the actual exposure in the packaging area.

Table 8. Mean cobalt TWA and STEL respiratory exposure of all the workers.

Cobalt respiratory exposure					
TWA-mg/m^3			**STEL-mg/m^3**		
Mean	**SD**	**P-Value**	**Mean**	**SD**	**P-Value**
0.254	0.374	0.597	**0.323**	0.565	0.729

The mean TWA of all the workers for all three sampling days was 0.254 mg/m^3. Total exposure in the packaging area is exceeding the 8 hour occupational cobalt exposure limit. Repeated measures ANOVA test showed that there is no statistical significant TWA exposure between the workers. The mean STEL of all workers over three sampling days was 0.323 mg/m^3, which also exceeds the STEL-guidance limit.

Repeated measures ANOVA showed that there is no statistical significant STEL exposure between the different workers.

A pair-wise correlation between the mean TWA and the total mean dermal exposure of each area was done. No correlations were found between the TWA and the different dermal exposure areas.

Table 9. Pair-wise correlations between TWA and dermal exposure areas

Pair-wise correlation between TWA and dermal exposure area.			
Variable	**Mean of anatomical area**	**R-Value**	**P-Value**
Mean TWA	Palm	0.412	0.588
Mean TWA	Back of hand	0.705	0.295
Mean TWA	Wrist	0.707	0.293
Mean TWA	Forehead	-0.316	0.684

DISCUSSION

The change in hydration indices throughout the shift was different for each anatomical area. The palm was very dry at the beginning of the shift and slightly dry at the end of the shift. The back of the hand was slightly dry from the beginning to the end of the shift. The hydration on the wrist increased from slightly dry in the beginning of the shift to normal. The wrist is the only area where the hydration indices differed significantly from the beginning to the end of the shift. A repeated measures ANOVA indicated significant differences of hydration indices on the forehead between the workers within the group. The change in hydration indices of the forehead was highly variable between workers at the beginning and end of the shift and does not indicate whether the hydration indices increased or decreased.

Workers wore long sleeve overalls and gloves while working in uncomfortable high temperatures thus increasing hydration on the skin. Kezic and Nielsen (2009) reported that hydration/occlusion of the skin is a mechanism, which can alter the skin barrier function. Increased skin hydration can occur when skin has been immersed in water for a long period or when evaporation is prevented/decreased for example when wearing a glove or protective clothing (Kezic and Nielsen, 2009).

By using the *in vitro* Franz cell system Larese Filon *et al*. (2004, 2007) showed that cobalt powders dissolved in synthetic sweat can release metallic ions (Co^{2+}), which permeate the skin. Hydration of the skin will also influence the ability of cobalt to permeate into the skin.

TEWL indices indicated a normal barrier function for the back of the hand, wrist and forehead at the beginning of the shift after which it deteriorated to low barrier function (strained skin condition) at the end of the shift. The TEWL indices on the palm of the hand indicated a low barrier function at the beginning of the shift after which it deteriorated to a very low barrier function (critical skin condition). The barrier function decreased significantly for the back of the hand, wrist and forehead from the beginning of the shift towards the end of the shift. The barrier function of the palm did not decrease significantly during the shift, although it was compromised before commencement of the shift.

Steady-state flow of percutaneous cobalt permeation is 0.0123 ± 0.0054 µg/cm^2/h, with a lag time of 1.55 ± 0.71 h (Larese Filon *et al*. (2004, 2007). Workers were exposed to high levels of cobalt during the shift, which is longer than the lag time. Permeation can take place although the permeation rate is low. Studies also proved that cobalt can permeate to a greater extent through damaged skin than intact skin (Larese Filon *et al*., 2009).

The Dalgard *et al*. (2003) self-reported skin questionnaire did not indicate the presence of skin disease. One worker reported scaly skin. All the workers reported troublesome sweating. Troublesome sweating may possibly be ascribed to the uncomfortable temperatures while working rather than indicating the presence of skin disease. This questionnaire is subjective to the workers own opinion about personal skin condition. The low scores suggest that workers believe that there skin is healthy and in good condition. The hydration and TEWL measurements indicate normal to slightly dry hydration levels and low to very low skin barrier functions, thus contradicting the self-reported score. The same contradiction was also found by Du Plessis *et al.* (2010) at a base metal refinery where workers were exposed to nickel.

Cobalt dust was visible on the clothes of the workers, so much so that they had to dust themselves off when taking a break and at the end of the shift. Worker 1 had to cut open the bulk bag and force cobalt into the funnel with a hammer and spade. The platform of worker 1 was a metal grid, which allowed cobalt to drop down onto

worker 2. The force of the cobalt released from the funnel into a 25 kg bag released cobalt into the air and the breathing zone of worker 2. Worker 2 manually assured the correct weight by using a scoop and scale. Worker 3 stood next to worker 2 when receiving the bags to be sealed. A small section of the funnel was eroded where cobalt escaped from. Since the eroded section was at a height, the cobalt could easily become airborne or drop onto worker 2 and 3. Housekeeping during and after the packaging is extremely poor. Considering all the cobalt exposure sources, dermal and respiratory exposure is inevitable.

The removal of skin contaminants method which was used has a removal efficiency of >90%. The OSHA Method ID125-G tested the efficiency on a glass surface. There is an obvious difference between sampling from human skin and a glass surface. *In vivo* validation of the sampling method is a limitation for all dermal sampling studies and results should be interpreted accordingly (Du Plessis *et al*., 2010). The efficiency of the method gives a good indication of how much cobalt is indeed loaded onto the skin.

Detectable levels of cobalt were present on the palm, back of the hand, wrist and forehead before the shift commenced. From observation, it is clear that cobalt was visible on many surfaces in the packaging area. Cobalt exposure is occurring as result of surface contamination and dermal contact, especially from airborne cobalt.

Dermal cobalt exposure increased significantly from before the shift towards the end of the shift for the palm, back of the hand and wrist. The forehead is the only area where dermal exposure did not increase significantly from the beginning of the shift towards the end. The palm is the only area where cobalt loading increased after the break. All the other anatomical areas had lower cobalt exposure at the end of the shift than during the break. It was observed that workers wore their gloves less frequently after the break than before, therefore the geometrical mean cobalt loading on the palm increased from 19.815 µg/cm^2 during the break to 23.070 µg/cm^2. It is possible that workers did not prefer wearing the gloves, and became less conscious of the necessity of wearing them towards the end of the shift. The Mine Health and Safety Act requires workers to wear PPE if an area is demarcated as a PPE zone. It is the responsibility of the worker to comply with this requirement. The employer is responsible to ensure that workers wear the PPE. Appropriate and comfortable PPE should be provided by the employer as far practicable.

The mean total dermal exposure is calculated by summating the mean exposure at the break and the mean exposure at the end of the shift. After removing cobalt at the beginning of the shift the skin is considered to be cobalt free. Cobalt on the skin at the break and end of shift represent the actual cobalt exposure from the packaging area. The mean total dermal exposure of the wrist and back of the hand ($p=0.001$, $r=0.999$) correlated significantly, while none of the other combinations of dermal exposed areas indicated a significant correlation. The palm and back of the hand ($p=0.072$, $r=0.928$), and the wrist and palm ($p=0.077$, $r=0.923$) are leaning toward a statistically significant correlation. In terms of planning future dermal cobalt exposure assessments, this correlation between the wrist and back of the hand can be taken into consideration when determining sampling areas.

Detectable cobalt was found on the 1 tonne bag, 25 kg bag and face of scale. The 25 kg bag were sampled just before the crates were sealed for shipment. European Commission Regulation no. 1907/2006 (REACH, 2010) requires that a chemical should not have an impact on health or the environment before it enters commercial use. The geometrical mean surface contamination on the 25 kg bags was 0.749 $\mu g/cm^2$, thus persons who will receive the packaged cobalt will also be exposed to the surface contamination. The surface contamination on these 25 kg bags are of concern as it does pose a possible health risk to the adverse health effects caused by cobalt salts.

To the best of the author's knowledge cobalt exposure has not been studied in cobalt packaging areas of base metal refineries. Cobalt dermal exposure studies are limited and little information is available to the knowledge of the authors to compare cobalt skin loading results of a similar study. Studies such as done by Liden *et al*. (2008) assessed dermal exposure to cobalt by means of acid wipe sampling, in different occupations (locksmiths, carpenters, cashiers and secretaries) and found dermal cobalt exposure to be 0.2 $\mu g/cm^2/h$ (1.6 $\mu g/cm^2/8h$).

Measurement of transepidermal water loss indicates the integrity of the skin barrier function (Verdie-Sévrain and Bonté, 2007). A decreased barrier function increases the absorption of a substance, which can result in sensitisation. An intact barrier function protects the integument system from absorbing potentially harmful substances into the body where it can act locally or systemically. Frequent contact with cobalt can cause allergic contact dermatitis (ACD). ACD is noted by two phases: (1) sensitisation and (2) elicitation. The host is firstly immunised to cobalt

and reintroduction of cobalt can elicit a type IV hypersensitivity reaction (Alenius *et al*., 2008).

Some individuals may be pre-disposed with an intrinsically affected skin barrier, which facilitates the absorption of substances into and through the skin barrier. Such individuals are more susceptible for local as well as systemic toxicity to exposure of a chemical (Kezic and Nielsen, 2009). Measurement of the transepidermal water loss of workers exposed to chemical substances can give a good indication as to the risk of the exposure, as well as indicate the difference in degree of risk of individual workers within a homogenous exposure group. The palms of workers had a compromised skin barrier function at the beginning of the shift. The palm was also the anatomical area, which had the highest cobalt exposure. The compromised skin barrier function and high cobalt exposure on the palm poses a high risk to develop ACD.

According to the Mine Health and Safety Act, 1996 (Act no. 29 of 1996) of South Africa (1995), Occupational Hygiene Regulation, the 8 hour occupational exposure limit (OEL) for cobalt and cobalt-compounds is 0.05 mg/m^3. The average exposure over three days for worker 1, 2 and 3 is: 0.475 mg/m^3, 0.244 mg/m^3, and 0.291 mg/m^3 respectively. Three of the workers are exposed above the OEL-TWA for all three sampling days. Cobalt exposure levels for worker 4 is the lowest. This is due to the fact that worker 4 is the furthest from the most significant cobalt sources. The high exposure levels are evidently related to the observations made of the high levels of visible airborne cobalt during the packaging process.

No OEL-STEL has been specified for cobalt and compounds of cobalt under the Mine Health and Safety Act. As guide when controlling short-term excursions in exposure, the concentration of three times the OEL-TWA is used (Belle and Stanton, 2007). STEL for worker 1 and 3 also exceeded the limit of 0.15 mg/m^3.

The statistical analysis with ANOVA proved that the TWA cobalt exposure differed significantly for all workers. STEL exposures were also not statistically significant as indicated by repeated measures ANOVA. Each worker is dedicated a different task which equals different exposures. Exposure also varied for each worker on the different sampling days. This proves that there is a flaw within the packaging process relating to engineering controls to limit cobalt exposure.

A pair-wise correlation was done between the mean time weighted average (TWA-mg/m^3) of all four workers and the total mean cobalt skin loading per anatomical area. The correlation was done to assess whether the dermal exposure increases with an increase in respiratory exposure. No correlations were found. The correlation had a limitation because the mean of the TWA and dermal exposure was used for the correlation, thus significant differences of individual exposures were lost.

CONCLUSION

High levels of dermal and respiratory cobalt exposure occurred in the cobalt packaging area by means of airborne cobalt, surface contamination and poor housekeeping. The hydration levels of skin of workers were slightly dry to normal. Skin barrier function of workers deteriorated significantly during the shift for all anatomical areas except the palm. The palms of workers have the highest risk, due to the low barrier function at beginning of shift and further deterioration to a very low barrier function at the end of the shift.

A compromised barrier function may facilitate the absorption of cobalt into the skin. PPE was not worn during the whole shift especially gloves, therefore increasing the dermal exposure. Surfaces in the packaging area are contaminated with cobalt as is evident by surface sampling and observations of poor housekeeping. Workers believe they have healthy skin, but the hydration and transepidermal water loss measurements indicate otherwise.

Workers are exposed above the respiratory occupational exposure limit of 0.05 mg/m^3 for cobalt. Short-term respiratory exposures are also exceeding the guidance limit. The high levels of respiratory exposure are due to high levels of airborne cobalt during packaging. Airborne cobalt is the obvious source of the high dermal cobalt exposures as well as surface contamination. The current engineering method of the cobalt packaging area is failing to contain the cobalt in such a way that does not expose workers to cobalt.

Recommended measures to lower cobalt exposures are as follows: i) Replace/review the current packaging process with a system, which will be able to contain cobalt in such a way that does not expose workers. The packaging system is outdated and newer packaging technology may protect workers against high cobalt exposure. A new packaging system will also be beneficial to lower surface contamination of the

25 kg bag before it enters commercial use. ii) Retrain and educate workers about health impacts of cobalt exposure, especially dermal exposure (allergic contact dermatitis) and the possible carcinogenicity of cobalt. iii) Review current PPE used, and provide comfortable equipment to encourage workers to protect themselves against exposure. iv) Train workers to use PPE effectively.

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CHAPTER 4

CONCLUDING CHAPTER

CONCLUSION

The skin conditions were assessed to determine if cobalt exposure did have an influence on the barrier function and skin condition. Hydration levels varied between slightly dry and very dry at the beginning of the shift for the palm, back of the hand and wrist. The wrist was the only area, which increased significantly at the end of the shift. Hydration indices for the forehead were highly variable between workers at the beginning and at the end of the shift.

Barrier function did decrease significantly from a normal barrier function to low barrier function most probably as result of the cobalt exposure on the back of the hand, wrist and forehead. The palms of workers had a low barrier function at the beginning of the shift and decreased to a very low barrier function although the results did not show a statistical significant change. Dermal exposure was high and increased significantly during the shift on the palm, back of hand and the wrist. The palm had the highest dermal exposure and the lowest barrier function. Work surfaces were contaminated and contributed to dermal cobalt exposure. A compromised barrier function together with high dermal exposure increases the risk of developing adverse health effects of cobalt.

Respiratory exposure exceeded the 8 hour occupational exposure limit for worker 1, 2 and 3. The STEL also exceeded the guidance levels for worker 1 and 3. The high levels of airborne cobalt does not only pose a risk to inhale cobalt but also increases the dermal cobalt exposure. The aims of this study to assess the dermal and respiratory exposure to cobalt and to assess the skin condition of the workers were achieved. The hypothesis that workers are exposed to dermal and respiratory exposure to cobalt in the cobalt packaging area of this base metal refinery is accepted.

Furthermore, workers in the packaging area were not aware of the adverse health effect cobalt may cause. It is important to educate workers so they understand why they have to follow procedures and wear personal protective equipment, otherwise it is a senseless exercise from an uneducated workers point of view to comply with safety requirements. Improved occupational hygiene practices are essential to

adequately manage the cobalt packaging area in such a way that the health of workers are not endangered.

RECOMMENDATIONS

Management and control of exposure to hazardous chemical substances is not only a South African legislative requirement it is also a social responsibility to ensure that the health of workers are not endangered. The following recommendations are made to reduce exposure and manage the health risk associated with exposure to cobalt:

Engineering controls

Engineering methods must be implemented to reduce exposure to cobalt. The manual handling to force cobalt out of the bulk bag, the force exerted by the gravity of cobalt in the funnel into the 25 kg bag and the manual weight assurance are examples of the mechanical process exposing workers to high levels of cobalt.

Ultimately, the machinery and procedures used to package cobalt at this packaging area is outdated compared to other new available packaging technologies. Considering the high respiratory- and dermal exposure, as well as related health effects due to cobalt exposure, it is worthwhile exploring other more practicable applications for packaging of cobalt, which will reduce the amount of exposure.

Recommendations on the current packaging system are made in Table 10. The recommended corrective action will reduce the airborne cobalt and subsequently reduce exposure to cobalt.

Table 10. Observations and recommended corrective actions to reduce airborne cobalt.

Source of airborne cobalt	**Recommended corrective action**
Worker 1 starts the packaging process by hammering the bulk bag to loosen the cobalt, and then cuts it open to release the cobalt into the funnel of the machine.	Local extraction ventilation at work area 1 will assist in reducing the amount of airborne cobalt.
A spade and hammer is used to loosen and release cobalt into the funnel. Manual loosening of the cobalt increases	Eliminate the use of hammer and spade by preventing compaction of cobalt in the bulk bags before packaging. Investigate

direct exposure of worker 1.	storage methods, which will reduce compaction of cobalt.
Worker 2 releases the cobalt from the funnel into 25kg bags for packaging. The force of the cobalt released out of the funnel into the bag causes cobalt to become airborne.	Revise the method for holding the empty 25 kg bag in place while filling such as attaching the bag tightly around the funnel. Or impose engineering controls such local extraction ventilation at work station 2.
Manual handling of cobalt during weight assurance of 25 kg bags with a scoop, increases airborne cobalt.	Local extraction ventilation at work station 2.
The platform on which worker 1 stands on is right above worker 2. The platform is a steel grid, all the airborne and uncontained cobalt is allowed to fall through the grid down to the work area of worker 2 and 3.	Replace the steel grid floor with a solid base floor to minimise exposure of worker 2.
The side of the funnel is eroded. Cobalt is released from an opening on the funnel at a height causing cobalt to trickle onto worker 2 and 3.	Inspection and servicing of defective equipment should be done on a regular basis.
The packaging process is operated in front of a door. This allows uncontrolled air currents make cobalt airborne.	Natural ventilation is important in terms of thermal stress. Assess weather conditions and discern if the doors need to be closed or open during the shift.
The housekeeping of the packaging area is poor, large amounts of cobalt is visible around the packaging area. The surfaces of the machinery are not cleaned which causes cobalt to accumulate on the workplace surfaces.	Compose a checklist of housekeeping problem areas as a post-inspection of the work area to enforce good practice.

Administrative methods

Some of the workers were exposed above the OEL for cobalt on all three sampling days. The Occupational Hygiene Regulations under the Mine Health and Safety Act, 1996 (Act no. 29 of 1996) state that the employer must establish and maintain a system of occupational hygiene measurements of all working places where exposure to hazardous chemical particulates are ≥ 10% of the OEL. It is recommended that a hygiene measurement program be implemented taking into account that the exposure to cobalt far exceeds the OEL and poses a high risk to the health of workers in the cobalt packaging area.

If a hazardous chemical substances exceeds the OEL it should be zoned as a respirator zone, but only after the levels of exposure are reduced to as low as reasonably practicable by means of engineering or administrative controls.

This respirator zone must be clearly demarcated and identified by notice boards indicating that the relevant area is a respirator zone and that respiratory protective equipment must be worn. No person may enter or remain in a respirator zone unless he or she is wearing the required respiratory protective equipment.

The exposure of the workers can also be controlled by introducing the following control measures:

a) Avoid the generation of excessive cobalt dust.
b) By constantly improving housekeeping.
c) Designated areas for drinking and smoking away from the workplace.
d) Limit the time a worker is exposed to the cobalt.
e) By introducing and implementing appropriate safe work procedures which shall include written instructions to ensure that:
    - Cobalt is safely handled, used and disposed of.
    - Machinery and work areas are kept clean.
    - Early corrective action regarding the exposure to HCS can be taken.
f) Employees need to be trained in the safe working procedures when working with hazardous chemical substances and the procedures need to be available in the workplace.
g) All containers containing cobalt needs to be clearly labelled.
i) Employees trained in the effective use of PPE.

Personal Protective Equipment

The required PPE worn by the workers include: dust mask (3M FFP2), safety glasses, Injati gloves (Pienaar Bros (Pty) Ltd, South Africa) and ear protection. Use of personal PPE to limit exposure is the least perfect method. Workers did not wear the dust masks or gloves during the whole shift. Engineering and administrative controls are the preferred methods of preventing or reducing exposure to hazardous chemical substances. Considering the high levels of exposure in this occupational setting, PPE is providing 'primary protection' to limit exposure to cobalt. Use of PPE to protect workers should not be relied on to be sufficient.

Currently the correct use of PPE is critical in the cobalt packaging area and therefore re-induction and training is suggested on the following topics to educate and increase awareness amongst workers:

- Health effects of cobalt.
- PPE as a basic safety requirement.
- Importance of using PPE.
- How to fit and wear a dust mask.
- How to remove PPE safely (especially gloves)

Surface contamination of packaged cobalt bags

The geometrical mean surface contamination on the 25 kg bags is 0.749 µg/cm^2. Some of the packaged cobalt is being exported to Europe, where the European Commission Regulation no. 1907/2006, requires companies to demonstrate that a chemical does not have an impact on health or the environment before it enters commercial use (REACH, 2010). Surface contamination of the 25 kg packaged cobalt is occurring. Manual wiping of bags to reduce cobalt surface contamination will only create another source of exposure. Preferably contamination of surface should be avoided. An updated packaging system may lower the surface contamination.

Limitations of the study

A small number of individuals participated in the study. These are the only workers involved directly with the packaging of cobalt. The exposure time is approximately 135 minutes per shift, however this is the actual exposure time per shift. More data

would have delivered more results to compare exposures with, but the data obtained is a reflection of the actual exposure.

Future studies

Detectable cobalt was found at the beginning of the shift, which may be attributed to many sources outside the packaging area. However, this finding did show that exposure to cobalt is not only the direct result of the cobalt packaging process. To obtain dermal exposure data representative of a particular process such as the packaging of cobalt, participants should be instructed to wash the intended sampling areas before the onset of new shift sampling. A dermal control sampling area is also recommended for future dermal occupational studies.