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Review

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Occupational respiratory exposure to platinum group metals: A review and recommendations

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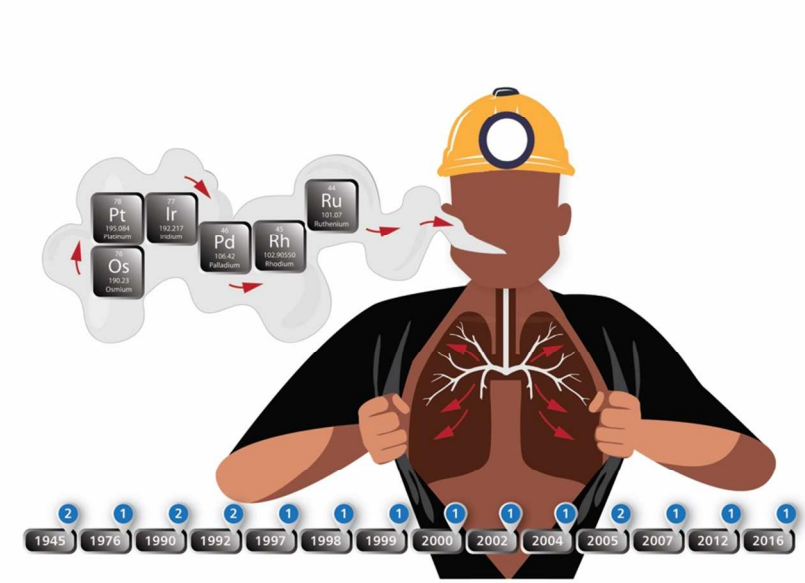
Table of content graphic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Abstract

Platinum Group Metals (PGMs) is a group of metals that include platinum, palladium, rhodium, ruthenium, iridium and osmium. Occupational respiratory exposure to platinum has been reported since 1945 but studies investigating occupational exposure to palladium, rhodium, ruthenium, iridium and osmium are scarce. This review provides a summation of the information available on the respiratory exposure to PGMs in various industrial settings, methods used to assess exposure and the possible adverse health effects resulting from occupational exposure to PGMs. Of these effects, respiratory sensitization caused by soluble PGMs is of most importance. Metallic PGMs have not been shown to cause allergic reactions. This review reiterates that occupational respiratory exposure to PGMs is dependent on the type of industry where exposure takes place, the chemical form (soluble or insoluble) of the PGMs present in the workplace air and the tasks performed by workers in the specific work areas. Sensitization to soluble platinum is associated with the degree of exposure to soluble platinum compounds and the highest concentrations of soluble PGMs in workplace air have been reported for precious metals refineries where personal exposures frequently exceed the occupational exposure limit for soluble platinum (2 $\mu g/m^3$). Additionally, this review emphasizes that personal exposure monitoring is preferred over area monitoring when assessing workers' exposure to PGMs. The legislation applicable to occupational exposure to PGMs is also discussed and it is highlighted that the occupational exposure limit for soluble platinum has remained unchanged, in most countries, since 1970 and that too few countries have classified PGM compounds as respiratory and/or skin sensitizers. Finally, recommendations are made to ensure that future investigations are comparable in terms of the type of exposure monitoring (personal or area) conducted, the

type of tasks included in the exposure monitoring program and the format in which results are reported.

Background

Platinum group metals (PGMs) is a group of rare metals that include platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os).[1] The main deposits of PGMs are found in South Africa, Russia, Zimbabwe, the United States of America, Canada and China.[2,3] PGMs occur together naturally and are commonly used in automotive emission control catalysts, dental appliances, electrical appliances, jewelry and anticancer drugs.[2,4,5] An increase in the use of automotive catalytic converters and the increased demand for electronic devices in the technologically developing world have resulted in an increase in the demand for these metals worldwide.[3,6] Particularly Pt, Pd and Rh have become valuable commodities as they are widely used as automobile exhaust catalysts to convert noxious gas emissions into more benign forms.[7] Tighter European Union emission limits and higher diesel automobile output has led to an increased demand for Pt in the automotive industry with the total demand for Pt in the European automotive sector forecast to rise by 7% in 2017 (the highest level since 2008) and the worldwide demand for Pt in automotive catalysts is forecast to rise by 2%. The demand for Pd is forecast to rise by 5%, mainly due to the automotive catalyst industry, while the demand for Rh in the automotive catalyst industry as well as industrial applications such as the glass, chemical and electrical sectors is also forecast to rise by 2-3%.[8]

In order to meet worldwide demands, workers in different industries such as mining, refining, catalyst production, chemical manufacturing, recycling and the petroleum industry are exposed to PGMs on a daily basis.[9-11] Workers in these industries are, therefore, at risk of developing adverse health effects associated with exposure to PGMs. These effects are well documented and may include occupational asthma, rhinitis, tight chest, sneezing, shortness of breath or allergic contact dermatitis.[4,12-14] Some of the PGM salts, such as the hexachloroplatinates, are among the

most potent sensitizers and allergens encountered in the workplace and respiratory sensitization to PGM-salts is a significant health problem in the PGM-industry.[15-17]

Occupational exposure to PGMs occurs mainly through inhalation[10] and this review aims to give a critical review of published studies on the respiratory exposure to PGMs in occupational settings. Studies that reported area or personal occupational respiratory exposure to PGMs are reviewed in order to highlight differences in: methodologies used; exposure levels in different industries; reporting methods and other factors that may influence occupational respiratory exposure to PGMs. Furthermore, recommendations are made for future studies in order to promote, amongst other things, consistent reporting of results and to facilitate comparisons between studies. The main aim of this review is not to discuss, in detail, PGM toxicology, adverse health effects caused by PGM exposure or environmental exposure to PGMs but to review occupational respiratory exposure to PGMs. Therefore, the topics mentioned above are only discussed briefly. For more information regarding these subjects the reader is referred to reviews published by the World Health Organisation[12], the UK Foods Standards Agency: the Committee on Toxicology[18], the European Commission Scientific Committee on Occupational Exposure Limits for Pt and Pt compounds[19], the Dutch Expert Committee on Occupational Standards[20] and the chapters on Pt[10], Pd[11], Rh[9] and Ir[21] in the "*Handbook on the toxicology of metals, Volume II*".[22]

Review method

Literature searches were performed using Scopus, Google Scholar and Science Direct with the search terms "platinum group metals", "occupational respiratory exposure to platinum group metals", "soluble platinum", "platinum salt sensitization", "platinum occupational exposure

limit", "soluble rhodium", "soluble palladium", "soluble iridium", "soluble ruthenium" and "soluble osmium". All publications up to 31/05/2017 were considered. This review includes publications which investigated occupational respiratory exposure to PGMs in primary or secondary PGM industries. Publications examining respiratory exposure to PGMs resulting from environmental sources such as automotive emissions or road dust, PGM exposure in the dental industry or exposure to antineoplastic drugs were excluded.

Routes of exposure

Inhalation of PGM containing particulate matter is of greater significance in terms of potential health risks compared to ingestion as a route of exposure.[7] The respiratory tract shows a higher PGM uptake compared to the digestive tract[23] and since inhalation is seen as the primary route of exposure to Pt salts, the majority of research regarding exposure has been performed on respiratory exposure. However Maynard et al.[24] suggested that the skin as a route of exposure might serve as an alternative exposure route for Pt salts and *in vitro* permeation studies have shown that Pt is permeable through intact human skin.[25,26] Heederik et al.[27] also stated that dermal exposure could be considered as an additional route of exposure in more comprehensive exposure assessments as it is unclear whether it plays a role in sensitization to Pt salts.

The main routes for occupational exposure to Pd, Rh and Ir are via inhalation and, to a lesser extent, the skin. Absorption through inhalation is of particular importance in the refining and automotive catalyst industries.[9,16] Similarly to Pt, *in vitro* permeation studies have also shown that Pd nanoparticles[28] and Rh is permeable through intact human skin[25,26,29] which suggests that the skin as a route of exposure may contribute to the total body burden of PGMs.

Table 1 summarizes the adverse health effects reported following occupational PGM exposure and contains examples of studies where adverse health effects or diseases of the respiratory tract and skin were reported following exposure to PGMs in various industries. This suggests that both the respiratory pathway and the skin must be considered as possible routes of exposure when investigating occupational PGM exposure.

Toxicology and health effects

Sensitization to the different soluble PGMs and their effect on the immune system is the most important hazard to the health of humans.[16,17,27] These and other adverse respiratory (rhinitis, tight chest, sneezing, shortness of breath) and skin (eczema, urticaria) health effects caused by exposure to PGMs as well as instances where positive skin prick or patch tests were observed are summarized in Table 1. Ru and Os were not included in Table 1 due to a lack of information available.

Platinum

The acute toxic effects of PGMs are dependent on metal speciation.[7,43] Toxicity evaluations of Pt have made distinctions between the toxicity of Pt and its salts on the one hand and the toxicity of Pt complexes which have medicinal (i.e. cis-platinum) or industrial applications (i.e. fuel catalysts) on the other.[18] The metallic form of Pt is considered to be biologically inert and non-allergenic[1,2] and there is no evidence of sensitization or adverse health effects.[12] On the contrary, some Pt salts, such as hexachloroplatinates and tetrachloroplatinates, are among the most potent sensitizers and allergens known[2] and represent the most hazardous chemical forms of Pt.[35] The allergic symptoms suffered by sensitized workers indicate a type I reaction mediated by IgE[27] and it is estimated that 1% of workers exposed to chloroplatinic acid worldwide becomes

sensitized annually. This usually leads to their permanent removal from even very low, short exposure and often removal from employment within the Pt industry.[15] Although the exact exposure circumstances that cause sensitization, or the risk factors for developing sensitization, are not yet known,[6,15] many studies have identified respiratory exposure to Pt salts, smoking[27,33,34,44,45] and atopy[27] as risk factors for the development of Pt salt sensitization. These studies demonstrated the link between the degree of respiratory exposure to Pt salts and the occurrence of Pt salt sensitivity and, therefore, highlight the need to quantify the concentration of Pt salts in workplace air in order to estimate the risk for sensitization.

Palladium

Epidemiological studies have shown that Pd ions are frequent reacting sensitisers.[16] Chemical and refinery workers are exposed to Pd salts during their daily tasks which may cause primary respiratory, skin and eye irritations.[4] Adverse health effects due to inhalation exposure and direct contact to palladium chloride have also been reported.[16] However, the UK Foods Standards Agency: Committee on Toxicology[18] stated that the Hazardous Substances Data Bank reported that despite the wide use of Pd, no occupational diseases have been shown. The lack of data on disease due to occupational exposure to Pd is reflected in the fact that only Finland has set an occupational exposure limit (OEL) for Pd.[46]

Other PGMs

Information on adverse health effects caused by the lesser known PGMs (i.e. Rh, Ir, Ru and Os) is rare and only a few cases of allergic reactions to Rh and Ir have been reported[9,13,17,41,42] (see Table 1). Positive skin prick test reactions for Rh have been reported in refinery and catalyst production workers.[9] In a case report by Merget et al.[17] an atopic operator in an electroplating

plant had positive skin prick tests for Rh and Pt following exposure to Rh salts. Since the sensitivity to the Rh salt was much higher, the authors concluded that Rh salts should be considered as occupational immediate-type allergens. De la Caudra and Grau-Massanés[41] and Goossens et al.[13] also published case reports of three workers (two jewelers and one refinery worker) who presented with occupational allergic contact dermatitis caused by Rh solutions or powders. Another case study reported Ir induced allergic occupational asthma where the diagnosis of Ir salt allergy was made in an electrochemical factory worker who was exposed to iridium chloride.[17,42]

Exposure-response and consequence of sensitization

The risk of developing hypersensitivity to soluble PGMs is predominantly correlated with intensity or degree of exposure.[47] Positive hypersensitivity reactions obtained by Santucci et al.[47] were only found in occupationally exposed workers and were not seen in non-occupationally exposed people living in urban areas. Other studies have also shown that the degree of exposure to soluble Pt is associated with the development of Pt salt sensitivity.[27,34,45] In general, the practice is to remove workers from areas of high exposure once they are sensitized to soluble PGMs. However, removing workers from areas of soluble Pt exposure does not necessarily mean that symptoms of occupational asthma will cease.[14,27,48] Merget et al.[14] showed that removing workers from areas where they are exposed to soluble Pt after they have already developed respiratory symptoms does not always prevent chronic asthma later in life. They recommended that removal from exposure should be done immediately following positive skin prick tests, irrespective of symptoms. However, since the degree of exposure to soluble Pt plays a significant role in the development of sensitization,[27] more emphasis should be placed on reducing the exposure of workers to soluble PGMs to as low as reasonably practicable through proper use of

engineering controls and the optimization of work methods. By automating processes and reducing manual handling of material, workers' exposure to soluble Pt can be reduced along with the risk of becoming sensitized, which will also reduce the number of workers who need to be removed from the workplace as a result of becoming sensitized. Hunter et al.[31] suggested that asthma caused by complex Pt salts could be prevented by not allowing these salts to reach the workplace atmosphere and that this could be achieved by the effective use of exhaust ventilation. The highest exposure to Pt listed in the published literature (5000-80000 $\mu g/m^3$) was recorded in an extremely poor ventilated refinery in China where workers were exposed to dust and spray of complex Pt salts and Pt metal.[19,49,50] This, along with evidence that the degree of exposure increases the risk for sensitization[27,34,45] suggests that reducing workers' exposure to Pt salts through proper control measures is the best way to reduce the occurrence of sensitization to Pt salts.

Occupational exposure

Platinum

There are three primary categories of industrial sources for exposure to Pt, namely mining, refining and processing,[50] and investigations into workers' occupational exposure to Pt salts have been conducted since 1945.[31,51] The information available regarding the effects of PGMs in humans was predominantly provided by occupational exposures in precious metals refineries,[27,33,45,52] however with the increased production of automotive catalysts, investigations have also been conducted in the automotive catalyst production industry.[6,34,53] Significant respiratory exposure to Pt compounds has been reported in production areas of refineries and automotive catalyst plants[45] and even though the concentrations of Pt reported for non-

production areas are lower than those obtained in production areas, they are still much higher than those reported for distant (non-exposure) areas.[6]

Other PGMs

Only a few studies have reported occupational respiratory exposure to Pd, Rh and Ir in refineries or automotive catalyst plants.[6,51,54-56] One study of note is Cristaudo et al.[6] which reported Pt, Pd, Rh and Ir concentrations in workplace air in an automotive catalyst production and recycling plant. Their results for personal exposure ranged between 0.003 and 5.75 μg/m^3 for Pd, between 0.0001 and 0.035 μg/m^3 for Rh and between 0.00006 and 0.002 μg/m^3 for Ir. Cristaudo et al.[35] reported that the prevalence of positive skin prick tests for Pd, Rh and Ir in an automotive catalyst manufacturing plant was very low and, during their investigation, only workers who were sensitive to Pt tested positive. Some studies have identified Pd allergies in refineries and automotive catalyst manufacturing plants[4] and Rh- and Ir-allergies have been identified in electrochemical and jewelry industries where workers came into close contact with solutions containing Rh or Ir.[17,41]

The findings from studies reporting occupational respiratory exposure to PGMs will be discussed in detail during later sections.

Non-occupational exposure

Although the concentrations of Pt measured in non-production areas of industrial plants are much lower than those measured in production areas, they are still 1000 times higher than concentrations measured in distant non-industrial areas.[53] In comparison to concentrations of soluble Pt in the indoor air of various workplaces, which is normally measured at μg/m^3 levels,

the soluble Pt content of environmental samples measured in cities are usually in the pg/m^3 range.[2] The increased use of PGMs as automotive catalysts have sparked interest in environmental exposure experienced by the general public and occupations such as tram drivers.[57] It has been demonstrated that the PGM concentrations present in airborne particulate matter in urban settings are significantly higher than that of rural settings where there are less emission sources[58] and over recent decades, the Pt, Pd and Rh content of airborne particulate matter in major cities have increased substantially.[9,10,16] The general population can also be exposed to low concentrations of Pt and Pd through jewelry and mucosal contact with dental restorations.[4,10] Nevertheless, it is unlikely that people from the general population, who are exposed to ambient concentrations of soluble PGMs at least three orders of magnitude lower than as seen in occupational settings, will develop similar adverse health effects.[12]

Exposure assessment and analysis methodology

In 1945, Hunter et al.[31] and Fothergill et al.[51] collected airborne particulate samples in precious metals refineries by drawing a known volume of air through a particulate filter during specific tasks or operations. These samples collected soluble Pt salts, Pt metal as well as other precious metals. For analysis Hunter et al.[31] used a colorimetric method while Fothergill et al.[51] used a combined chemical and spectrographic method. These two methods were used at the same sampling points in one of the refineries and similar results were obtained.[31] Over thirty years later, Johnson et al.[54] reported Pt and Pd concentrations in environmental samples collected in mining and refinery areas on glass fiber filters with hi-volume air samplers which sampled continuously over 14 days. Baker et al.[33] reported area Pt salt exposure from environmental monitoring data gathered between 1977 and 1979 in a secondary Pt refinery. However, the exact monitoring procedure was not disclosed.

In 1985, the Occupational Safety and Health Administration (OSHA) and the Health and Safety Executive (HSE) published methods [OSHA ID-130SG and Methods for the Determination of Hazardous Substances (MDHS) 46, respectively] for the determination of exposure to Pt in workplace atmospheres.[59,60] Since then, the measurement of soluble Pt or Pt metal in workplace air has involved drawing air at approximately 2 l/min through a mixed cellulose ester (MCE) filter which is connected to a sampler designed to collect the inhalable particulate fraction.[59-64] It has to be noted however, that methods such as the MDHS 46 cannot differentiate between different chemical species, which might be problematic since different chemical species of soluble Pt are more potent allergens compared to others.[65] Since 1985, the HSE has published the updated MDHS 46/2 method and the OSHA and the National Institute for Occupational Safety and Health (NIOSH) have published methods for the determination of exposure to metals or elements (including Pt and Pd) in workplace air.[61-63,66] The most recent guideline methodology for the measurement of Pt in workplace air was described by the International Platinum Group Metals Association (IPA).[64] Table 2 summarizes the sampling methods available to determine personal exposure to soluble and insoluble Pt compounds in workplace air.

Analytical methods such as graphite furnace atomic absorption spectrometry (AAS-GF), inductively coupled plasma-mass spectrometry (ICP-MS) and inductively coupled plasma-atomic emission spectroscopy (ICP-AES) have been used to quantify Pt compounds in various media.[12,63] Most of the available methods are only validated for the analysis of Pt while the NIOSH 7303 method is validated for Pt and Pd.[62] As indicated in Table 2, the limit of detection (LOD) differs for all of the available methods with the sensitivity of the methods increasing with time. For example the MDHS 46/2 method, published in 1996, reported a LOD for Pt of 1 – 4 $\mu g/m^3$ for a 30 liter air sample (15 minutes at 2 l/min) while the IPA Harmonized Methodology

for the Sampling of Pt in Workplace Atmospheres, published twenty years later, reported a LOD of 0.0027 μg/m^3 for a 30 liter air sample.[60,64,66]

Area versus Personal measurements

The methodologies listed in Table 2 can be used to determine personal exposure of workers to PGM compounds. Various PGM exposure investigations have also collected area measurements where the concentration of PGMs in the general workroom air was determined.[6,34,68] Cristaudo et al.[6] described area and personal measurements collected in different areas of an automotive catalyst production plant. Correlations performed between the PGM content of area measurements and personal measurements revealed very strong positive correlations for Pt ($r=0.983$, $p<0.001$) and Pd ($r=0.961$, $p<0.001$). A similar observation was made by Vos et al.[68] where the refinery worker with the highest personal soluble Pt exposure was working in the area where the highest area soluble Pt concentration was measured. Nevertheless, Vos et al.[68] reported that the mean area soluble Pt concentrations (0.583 μg/m^3) were significantly lower than mean personal exposures to soluble Pt (1.813 μg/m^3) for tasks where personal and area measurements were collected simultaneously. Subsequently the authors concluded that area soluble Pt concentrations were not an effective indicator of personal exposure. Merget et al.[34] also reported higher Pt concentrations for personal sampling compared to area sampling, and mean concentrations of Rh in personal measurements (0.035 μg/m^3) collected by Cristaudo et al.[6] in the coating department was much higher than that of area measurements (0.002 μg/m^3). These studies indicate that area measurements cannot be used to indicate personal exposure and that personal exposure measurements are preferred when assessing workers' exposure to PGMs. Collecting personal exposure measurements instead of area measurements also provides the investigator with the extra benefit of being able to compare the exposures to the OEL.

Occupational exposure limits (OELs) and associated notations

Soluble platinum

In 1963, the American Conference of Governmental Industrial Hygienists (ACGIH) adopted the threshold limit value-time weighted average (TLV-TWA) for soluble Pt salts of 2 μg/m^3, over an 8-hour shift. In 1970, it was revised to the TLV-TWA of 2 μg/m^3, for soluble Pt salts (*measured as Pt*) which is presently still in use.[27,69] The same exposure limit has been used by the OSHA (United States of America) as permissible exposure limit (PEL) since as early as 1974.[70] Currently, most countries with a Pt industry still impose this 8-hour time weighted average (TWA) respiratory OEL of 2 μg/m^3 for water-soluble Pt species. Although it is one of the lowest limits for workplace respiratory chemical exposure,[15] sensitization was reported to be occurring at concentrations below 2 μg/m^3 and as a result, in 1991, a World Health Organization (WHO) task group considered recommending an even lower OEL. However, there was not sufficient exposure-response data available to justify a reduction in the OEL and they, subsequently, recommended that the OEL of 2 μg/m^3 be changed from an 8-hour TWA to a ceiling value which may not be exceeded at any time during the shift.[12]

In 2000, the Japan Society for Occupational Health (JSOH) established a TWA-OEL of 1 μg/m^3 for soluble Pt (as Pt)[71] and in 2008, the Dutch Expert Committee on Occupational Standards (DECOS) recommended a health-based 8-hour TWA-OEL of 5 ng/m^3 (as Pt) for chloroplatinates as inhalable dust.[20,27] Despite some species of soluble Pt (i.e. chloroplatinates) being more potent allergens compared to others, most countries/organizations list the OEL of 2 μg/m^3 as being applicable to "soluble Pt salts".[65] The HSE (United Kingdom), however, does not use a generic description in its list of workplace exposure limits (WELs). Instead, they exclude certain

halogeno-Pt compounds from the classification of soluble Pt compounds as they are not potent sensitisers.[65,72]

A number of studies have reported that respiratory exposures of workers frequently exceeded the OEL of 2 μg/m^3 and it is possible that this workplace limit alone is not completely protective and that sensitization can occur at exposure levels much lower than the OEL.[12,15,24,27,45,65,68] Because of this, the DECOS proposed an 8-hour TWA-OEL for chlorinated Pt salts of 5 ng/m^3, which is 400 times lower than the current OEL.[15,20,27] This recommendation was based solely on a 5-year prospective cohort study by Merget et al.[34] and has sparked controversy because the authors, themselves, stated that the results from the study could not be used to define a valid cut-off value for an OEL.[15,27] Since occupational exposure to soluble Pt still frequently exceeds the OEL,[27,68] it seems unlikely that high exposure industries, such as refineries, will be able to comply with the proposed OEL. However, the fact that the OEL for soluble Pt has remained unchanged since 1970 questions whether the limit is still relevant and whether or not it is capable of protecting workers from developing adverse health effects. This has lead the IPA and its member companies to implement a best practice exposure limit of 0.1 μg/m^3 for soluble Pt exposure in order to better protect their workers from the adverse health effects associated with exposure to soluble Pt (Cas Badenhorst, personal communication).

Table 3 gives a summary of the countries which have used sensitization notations to classify soluble Pt compounds as respiratory and/or skin sensitizers. Only seven of 20 countries or organizations, included in this review, have classified soluble Pt compounds as sensitizers. However, the manner in which countries classify chemicals as sensitizers differ from one another in that some countries only classify respiratory sensitizers, while others acknowledge that chemicals can cause respiratory or skin sensitization but do not specify which chemical causes

which type of sensitization and others classify chemicals as either respiratory or skin sensitizers or as both.

Insoluble platinum

The majority of countries, with the exception of the United Kingdom and South Africa (5 mg/m^3), have adopted an 8-hour TWA-OEL of 1 mg/m^3 for insoluble Pt metal which is considerably higher than that of soluble Pt compounds.[63,72,73,79] The reason for this being that exposure to metallic Pt has not been associated with the development of allergic symptoms or other diseases.[20]

In addition to a TWA-OEL for soluble Pt (2 $\mu g/m^3$) and Pt metal (5 mg/m^3), the Department of Minerals and Resources (DMR) in South Africa has set a TWA-OEL of 3 mg/m^3 for respirable Pt mine dust measured in Pt mines.[74]

Other PGMs

Finland is the only country that has assigned an OEL to Pd compounds (0.5 mg/m^3 for insoluble Pd and 1.5 $\mu g/m^3$ for soluble Pd)[46] and the German Research Foundation has classified palladium chloride as a skin sensitiser.[78]

In general, the TWA-OELs for insoluble (metallic) and soluble Rh compounds set by countries or organizations are lower than those for Pt compounds. Most countries or organizations have assigned a TWA-OEL of 1 $\mu g/m^3$ for soluble Rh compounds and 0.1 mg/m^3 for insoluble Rh compounds.[46,72-74,76] The German Research Foundation has classified Rh as a suspected carcinogen[78] and the ACGIH has classified it as "non-classifiable as a human carcinogen due to a

lack of evidence".[79] The JSOH has classified Rh as a substance that will probably induce allergic reactions in human skin.[71]

Exposure studies in occupational settings

Occupational exposure to airborne soluble Pt has been reported for a variety of workplaces which include refineries, automotive catalyst production plants, recycling plants and metal coating facilities.[10] Conversely, studies reporting occupational exposure to airborne Pd, Rh and Ir are limited with only a few studies investigating occupational exposure to these metals.[6,53,54,56]

Platinum

Results from published studies investigating occupational respiratory exposure to soluble Pt were collated and compared in Figure 1 in order to show in which industries the highest concentrations of soluble Pt exposure were reported. For additional detailed information, the reader is referred the chapter on Pt[10] in the "*Handbook on the toxicology of metals, Volume II*".[22] Studies included in Figure 1 report results from personal and area measurements collected in different industries. Only studies reporting soluble Pt concentrations were included, since the soluble form produces greater adverse health effects.[10] Selected studies that reported occupational exposure to total (metallic and soluble) Pt, or that only reported the percentage of personal exposure measurements which exceeded the OEL or where a geometric mean could not be calculated were excluded from Figure 1. These studies are briefly discussed in the text only.

As is shown in Figure 1, the highest exposures to soluble Pt have occurred in refineries and respiratory exposures of refinery workers frequently exceeded the OEL of 2 μg/m^3.[27,45,68] Figure 1a shows personal exposures to soluble Pt as reported by the various exposure studies. In all of

the investigations conducted in refineries (a-h), the maximum personal exposures exceeded the OEL of 2 μg/m^3 and most studies reported maximum exposures exceeding 10 times the OEL. All of the geometric means recorded for refineries in Figure 1a are below 0.05 μg/m^3 which suggest that, in refineries, the majority of personal exposures are low and that only a small percentage of measurements actually exceed the OEL, although those excursions can be over 50 times the OEL. The studies conducted solely in automotive catalyst production plants, recycling plants and metal coating plants (i-l), reported much lower soluble Pt personal exposure results than those conducted in refineries.

Figure 1b contains concentrations of soluble Pt from area measurements as reported in various studies. Most of the geometric means for studies conducted in refineries (a-l) exceeded 2 μg/m^3 while all of the concentrations reported for automotive catalyst and recycling plants were below 2 μg/m^3.

The exposure studies that could not be included in Figure 1 are summarized in the following text:

i. Johnson et al.[54] reported mean concentrations of total Pt from area measurements which were collected continuously over five working days. The measurements were collected in a Sudbury mine's precious metals area (0.377 μg/m^3) as well as the refinery section (0.159 μg/m^3) and in the salts section (0.180 μg/m^3) of a precious metals refinery.

ii. Brooks et al.[48] investigated Pt salt sensitization among Pt refinery and recycling workers and reported that the OEL for soluble Pt (2 μg/m^3) was exceeded 50-70% of the time.

iii. Schaller et al.[80] reported occupational exposure to total Pt in catalyst manufacturing and recycling industries. They reported mean concentrations of 5.1 μg/m^3 (range: 0.3-19.9 μg/m^3;

n=19) in the catalyst production area and 2.1 μg/m^3 (range: 1.8-3.1 μg/m^3; n=16) in the mechanical treatment area.

iv. Schierl et al.[81] conducted area and personal air sampling to determine workers' exposure to airborne Pt in a Pt refinery and catalyst production company. They reported mean concentrations of 1.1 μg/m^3 (range: 0.2-3.4 μg/m^3) for area measurements and 2.5 μg/m^3 (range: 0.8-7.5 μg/m^3) for personal measurements.

v. Linnett and Hughes[65] investigated the potential of different soluble Pt species to provoke allergic reactions in refinery workers. They reported results from personal and area soluble Pt measurements collected in a PGM refinery, a tetraammine platinum trichloride (TPC) laboratory and an automotive catalyst plant. At the PGM refinery 5.1% of 8573 measurements exceeded the OEL (2 μg/m^3), while at the TPC laboratory, 48.3% of 511 measurements and 28.7% of the 453 measurements at the automotive catalyst production plant, exceeded the OEL. Although the soluble Pt exposures measured at the TPC laboratory and the automotive catalyst production plant were significantly higher compared to the PGM refinery, the incidence of chloroplatinate allergy at the PGM refinery was higher compared to the other areas. Therefore, the authors concluded that TPC is not allergenic under normal industrial conditions and that the specific species of soluble Pt is very important since it will influence the degree of the adverse health effects experienced by the workers.

vi. Merget et al.[34] aimed to assess exposure to Pt salts and the incidence of Pt salt allergy in an automotive catalyst production plant and reported that 4% of 78 personal exposure measurements collected in high-exposure areas exceeded the OEL of 2 μg/m^3. In low exposure areas within the plant, they reported concentrations of below 10 ng/m^3 and 30-90 pg/m^3 in areas

outside of the plant. Since no incidences of sensitization were observed in workers with low exposure, the authors concluded that exposure to concentrations of soluble Pt below 10 ng/m^3 might be considered safe.

Palladium, rhodium and iridium

Although occupational exposure to Pd, Rh and Ir originating from environmental sources such as road dust have been reported,[82] only a few studies have reported occupational exposure to soluble Pd, Rh and Ir originating from industrial sources:

i. Fothergill et al.[51] reported concentrations of airborne Pd ranging from 0.3 to 32 μg/m^3 (mean = 4.99 μg/m^3; n = 10) during various tasks in a precious metals refinery.

ii. Johnson et al.[54] reported a mean concentration of Pd in a Sudbury mine's precious metals area of 0.291 μg/m^3 as well as mean Pd concentrations from area measurements collected continuously over five working days in a precious metals refinery [0.085 μg/m^3 (refinery section) and 0.028 μg/m^3 (salts section)].

iii. Kielhorn et al.[4] reported four personal exposure Pd measurements collected during the production of Pd compounds in 1996 (range: 0.38-11.6 μg/m^3). Another four Pd measurements were collected during 2000, two of which were short term measurements (< 0.5 and 3.1 μg/m^3) and two were 8-hour TWA measurements (28 and 128 μg/m^3).

iv. Petrucci et al.[55] reported concentrations of total PGMs in airborne particulate matter in various areas of an automotive catalyst production plant. The results ranged from 0.006 to 2.1 μg/m^3 for Pd, 0.001 to 0.003 μg/m^3 for Rh and 0.00005 to 0.002 μg/m^3 for Ir.

v. Violante et al.[56] and Cristaudo et al.[6] reported results of area measurements and personal exposure to the lesser known PGMs in various areas of an automotive catalyst production plant. Violante et al.[56] reported personal exposure to total Pd that ranged from 0.001 to 7.90 μg/m^3, while area Pd measurements ranged from 0.002 to 10.6 μg/m^3 for PM_{10} and from 0.03 to 11.0 μg/m^3 for total Pd. Cristaudo et al.[6] reported the mean personal measurements that ranged from 0.0001 to 0.035 μg/m^3 for total Rh and from 0.00006 to 0.002 μg/m^3 for total Ir. They also reported area PM_{10} measurements that ranged from 0.001 to 0.003 μg/m^3 for Rh and from 0.00005 to 0.002 μg/m^3 for Ir.

Factors that influence occupational respiratory exposure

Occupational respiratory exposure to PGMs can be influenced by a variety of factors such as the processes and tasks associated with the specific industry where exposure occurs and the chemical form to which workers are exposed.

Industry types

The degree of exposure to PGM compounds differs between different industries. As is shown in Figure 1, the exposure to soluble Pt in refineries is generally higher than in catalyst production or chemical plants.[10,24,34] This is very well demonstrated by Maynard et al.[24] (studies a, i and l in Figure 1a), who measured full shift (8-hours) as well as task-based personal exposure to soluble Pt at a refinery, an automotive catalyst production plant and a metal coating facility. The mean exposure results from the refinery (8-hour = 2.163 μg/m^3; short term = 2.531 μg/m^3) were considerably higher than that from the automotive catalyst production plant (8-hour = 0.216 μg/m^3; short term = 1.000 μg/m^3) or the metal coating facility (8-hour = 0.017 μg/m^3; short term = 0.090 μg/m^3). Only the measurements collected over 8 hours are shown in Figure 1a.

Species

The soluble fraction of PGMs in airborne particulate matter in each work area can differ tremendously from one area to another and can impact the degree of exposure to soluble PGMs experienced by the workers.[53,56] Cristaudo et al.[6] (study k in Figure 1a) reported the highest exposure to Pt in the coating department while the highest exposure to Pd was measured in the recycling and chemical catalyst departments. The mean soluble PGM fraction measured in all of these areas differed from one another. For example the samples from the coating department contained 30.1% soluble Pt and 36.1% soluble Pd and the samples from the chemical catalyst department contained 8% soluble Pt and 63.3% soluble Pd. This meant that workers in areas with PGMs which contained higher fractions of their soluble forms had an increased risk of exposure to soluble PGMs and PGM sensitization compared to other areas where higher fractions of the PGMs were insoluble. Furthermore, Linnett and Hughes[65] identified some soluble species of Pt to be more allergenic compared to others. Therefore, since the chemical form of Pt and other PGMs can have a substantial effect on the severity of the adverse health effects caused by exposure,[6,43,65] identifying the chemical specie to which workers are exposed to is of great importance when conducting investigations into occupational PGM exposure.

High exposure tasks and areas

Hunter et al.[31] reported concentrations of Pt in different work areas in four precious metals refineries (studies a-d in Figure 1b). These area measurements ranged from 0.9 to 1700 $\mu g/m^3$ with the maximum measurement of 1700 $\mu g/m^3$ (study number c in Figure 1b) recorded in an area where ammonium hexachloroplatinate was crushed. Fothergill et al.[51] reported airborne concentrations of Pt and Pd in different work areas of a precious metals refinery which ranged

from 0.9 to > 68 μg/m^3 for Pt (study number e in Figure 1b) and from 0.3 to 32 μg/m^3 for Pd. The maximum concentration Pt was measured during discharging of ammonium hexachloroplatinate from drying ovens and the maximum concentration Pd was measured during hand crushing and packing of diammine dichloropalladium. Both these studies reported handling and crushing of dry salts as tasks where airborne concentrations were increased compared to other areas in the refinery. Hunter et al.[31] indicated that incidences where workers complained of asthma were the highest in areas where workers came into contact with complex Pt salts in their dry form. Calverley et al.[45] reported that 27% of 566 Pt salt exposure measurements collected from production workers in a refinery exceeded the OEL of 2 μg/m^3 and that none of the measurements collected from non-production occupations exceeded the OEL. In a more recent study conducted in a precious metals refinery during non-routine operations, the personal exposure of production workers to soluble Pt ranged from 0.010 to 20.479 μg/m^3 (study number b in Figure 1a) where the maximum concentrations occurred during cleaning activities (cleaning draught lines and glove boxes).[68] During the same study, engineering (study number c in Figure 1a) workers were also exposed to soluble Pt (0.004 – 3.916 μg/m^3) during dismantling activities. In studies conducted in automotive catalyst production plants (studies j and k in Figure 1a), the highest concentrations of soluble Pt were recorded in the coating departments where Pt salt solutions were used to coat catalytic supports and impregnation areas where devices were impregnated with Pt salt.[6,34,53] Therefore, differences in the tasks performed in different working areas can have a substantial influence on exposure experienced by workers.

Heederik et al.[27] analyzed personal soluble Pt exposure measurements from five Pt refineries, retrospectively (studies d-h in Figure 1a). Between 135 and 463 measurements from each refinery were analyzed. The distribution of the results was highly skewed to the right and two of

the refineries' 95th percentile measurement was still below the OEL while all five refineries' 75th percentiles were below half of the OEL. This showed that these refineries contained a few high exposure tasks or areas while the majority of tasks or areas were associated with exposure below the OEL. Therefore, since the exposure profiles of different PGMs will differ between different work areas and during different activities, it is vital that workers with a variety of job titles, working in different work areas, performing routine and non-routine tasks, be monitored during a PGM exposure investigation in order to identify high exposure tasks and to obtain an accurate representation of the exposure experienced by workers in the specific occupational setting.

Differences in reporting of PGM exposure

Exposure data from available sources regarding PGM exposure in workplaces may not be directly comparable due to differences in sampling and analytical techniques.[50] It was apparent that the means in which research papers reported workers' respiratory exposure to PGMs differed from one another. Some papers focused on the medical surveillance of workers with Pt salt sensitivity, and reported the percentage of personal or area soluble Pt measurements which exceeded the OEL of 2 μg/m^3,[45,48,65] or divided the workplaces into low and high exposure areas.[34] This made it difficult to compare the concentrations of soluble PGMs measured with other studies where minimum, maximum and mean values were reported.

Furthermore, styles of reporting which species of the individual PGMs (soluble or metal) were measured differed between studies. For example, some papers reported concentrations of the individual soluble PGM measured[24], while others reported the concentrations of total individual

PGM (metal and soluble), which were measured, along with the percentage of soluble species.[6,53] Other papers only reported concentrations of individual PGMs in the air of workplaces.[55]

Differences in the reporting of exposure data hinder the comparison of data with those of other studies. As a result, recommendations are made in the following section to promote uniform reporting of data and stimulate effective comparison of exposure data from various sources.

Recommendations

i. Merget et al.[34] and Vos et al.[68] both collected personal and area measurements where the results from the personal exposure monitoring were higher compared to the results from the area monitoring and Vos et al.[68] stated that results from area monitoring should not be used to predict personal exposure. It is, therefore recommended that, if possible, personal exposure monitoring should be performed instead of area monitoring in order to get a more accurate representation of the exposure to soluble PGMs experienced by workers.

ii. The concentrations of PGMs reported by various studies, such as Maynard et al.[24], differed between different work areas and between different activities. Personal exposure to soluble PGMs was also reported to exceed the OEL during non-routine activities.[68] It is recommended that a variety of work areas and non-routine tasks be included in exposure assessments as they can often be overlooked when assessing exposure.

iii. It was noted that research papers reported the exposure monitoring results in a variety of ways, depending on the main focus of the study (i.e. medical surveillance or degree of exposure). In order to easily compare exposure monitoring results with other studies, it is recommended that authors report the number of measurements collected, minimum, maximum, arithmetic mean or

geometric mean concentrations of measurements collected in specific work areas (e.g. n= 13; min = 0.004 μg/m^3; max = 11.605 μg/m^3; arithmetic mean = 1.704 μg/m^3; geometric mean = 0.387 μg/m^3; area = bagging department of a precious metal refinery).

iv. It is recommended that the chemical form (metallic or soluble) of the particular PGM measured is clearly stated as it will have a considerable effect on the manner in which the results are interpreted.

v. Respiratory sensitization is the most significant adverse health effect following respiratory exposure to soluble PGM compounds,[19] yet only some countries/organizations (United Kingdom, South Africa, Sweden, Australia, Germany, British Colombia, and Japan) have classified soluble Pt compounds as respiratory and/or skin sensitisers.[71-73,75-78] Only Germany has classified Pd(II) compounds as skin sensitizers and only Japan has classified Rh compounds as possible skin sensitisers.[71,78] It is recommended that more countries and organizations classify soluble PGM compounds (especially soluble Pt) as respiratory and/or skin sensitizers in order to emphasize of the risk involved in working with these compounds.

Conclusion

Many studies have reported occupational exposure to Pt but studies reporting occupational exposure to Pd, Rh and Ir are scarce since these PGMs are not as potent allergens as Pt. The highest concentrations of airborne Pt have been measured in precious metals refineries where personal exposure to soluble Pt frequently exceeded the TWA-OEL of 2 μg/m^3. It is clear that the risk of becoming sensitized to soluble Pt is associated with the degree of exposure experienced by workers and this review indicated that occupational respiratory exposure to PGMs is dependent on the type of industry where exposure takes place, the chemical form

(soluble or insoluble) of the PGMs present in the workroom air and the tasks performed by workers in the specific work areas.

Furthermore, area measurements should not be used instead of personal measurements to indicate the PGM exposure experienced by workers and a variety of areas and tasks (routine and non-routine) should be monitored in order to identify the scenarios where the risk for sensitization is the highest. Also, consistent reporting methodologies are needed as it will allow for meaningful comparisons to be made between various studies. It is also important that the chemical form of the PGM which was measured be reported since it will have a substantial effect on the manner in which the results are interpreted.

There are limitations to the legislation regarding occupational exposure to PGMs with many publications arguing that the current OEL (2 $\mu g/m^3$), which has been in use since 1970, is not protective of worker health and that sensitization can occur at exposure below this level. In addition, only a few countries/organizations have classified PGM compounds as respiratory and/or skin sensitizers although they are known to cause sensitization.

Finally, it was noted that inhalation should not be the only route of exposure considered when assessing occupational exposure to PGMs. Pt, Pd, Rh and Ir have been shown to cause adverse dermal health effects and *in vitro* studies have shown that Pt, Pd (nanoparticles) and Rh permeates through intact human skin.

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Abbreviations

AAS-GF, graphite furnace atomic absorption spectrometry; ACGIH, American conference of governmental industrial hygienists; DECOS, Dutch expert committee on occupational standards;

HSE, health and safety executive; ICP-AES, inductively coupled plasma-atomic emission spectroscopy; ICP-MS, inductively coupled plasma mass spectrometry; Ir, iridium; IgE, immunoglobulin E; IOM, institute for occupational medicine; IPA, international platinum group metals association; JSOH, Japan society for occupational health; LOD, limit of detection; MCE, mixed cellulose ester; MDHS, methods for the determination of hazardous substances; NIOSH, national institute for occupational safety and health; OEL, occupational exposure limit; OSHA, occupational safety and health administration; Os, osmium; Pd, palladium; $PdCl_2$, palladium chloride; PEL, permissible exposure limit; PGM, platinum group metal; Pt, platinum; PVC, poly vinyl chloride; Rh, rhodium; Ru, ruthenium; TPC, tetraammine platinum trichloride; TLV, threshold limit value; TWA, time weighted average; WEL, workplace exposure limit; WHO, world health organization;

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Headshots & biographies

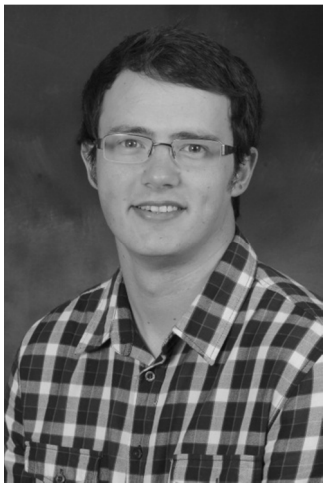

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Table 1. Summary of health effects caused by individual soluble PGMs in occupational settings.

PGM	Industry	Diagnosis	Health effect				Reference
		Positive skin prick or patch test	Respiratory sensitization / Asthma	Rhinitis, tight chest, sneezing, shortness of breath	Allergic contact dermatitis	Other skin adverse effects	
Pt	Handling paper treated with complex Pt salts in a photographic studio	-	-	X	-	-	12,30
	PGM refinery	-	X	X	X	X	12,31
	PGM refinery and laboratory	X	X	-	X	-	32
	Secondary PGM refinery	-	X	-	X	-	33
	Automotive catalyst production	X	X	X	X	-	34
	Automotive catalyst production	X	X	X	-	X	35
	Industrial exposure to chloroplatinates	X	X	-	X	-	36
	PGM refinery	X	X	-	-	-	27
Pd	PGM refinery	X	X	-	-	-	4,37
	PGM refinery	-	X	-	-	X	4,38
	Automotive catalyst production	X	X	-	-	-	4

Table 1. continued

PGM	Industry	Diagnosis	Health effect				Reference
		Positive skin prick or patch test	Respiratory sensitization / Asthma	Rhinitis, tight chest, sneezing, shortness of breath	Allergic contact dermatitis	Other skin adverse effects	
Pd	Chemist and metal workers	-	-	-	X	-	4
	Metal coating	X	X	X	-	-	4,39
	Palladium chloride ($PdCl_2$) fumes from an electrolysis bath	-	X	X	-	-	16
	Direct contact with Pd compounds	X	X	-	-	-	16
Rh	Rh plating at a goldsmith	X	-	-	X	-	40,41
	Electrochemical factory	X	X	X	-	-	17
	Refining, jewellery and dental industries	X	-	-	X	X	13,36
Ir	Electrochemical factory	X	X	X	-	X	17, 42

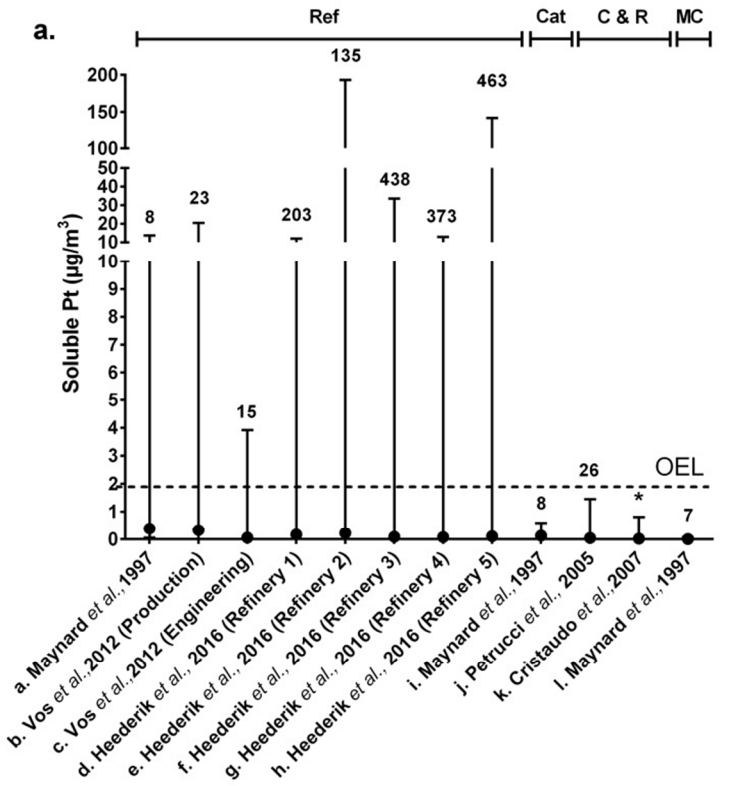
Table 2. Summary of inhalable fraction sampling methods used to measure personal respiratory exposure to PGMs.

Method	Sampling media and pore size	Sampling head and flow rate	Analytical technique	LOD	Reference
OSHA ID-130SG Pt in workplace atmospheres	MCE 0.8 µm	Cassette 2 l/min	AAS-GF	0.01 µg/ml	20,59,66
MDHS 46/2 Pt metal and soluble Pt compounds in air	MCE 0.8 µm	IOM sampler [a] 2 l/min	ICP-MS or AAS-GF	1 – 4 µg/m^3 (30 l air sample)	20,60,66
OSHA ID-121 Metal and metalloid particles in workplace atmospheres (atomic absorption)	MCE 0.8 µm	Cassette 2 l/min	ICP-AES or AAS-GF	2 µg/ml	61,66
NIOSH 7303 Elements (incl. Pt and Pd) by ICP (Hot block/HCl/HNO_3 digestion)	MCE 0.8 µm	Cassette 1 – 4 l/min	ICP-AES	0.38 (Pt) 0.75 (Pd) µg/sample	20,62
NIOSH 7302 Elements (incl. Pt) by ICP (Microwave digestion)	MCE 0.8 µm	Cassette 1 – 4 l/min	ICP-AES	8 µg/sample	63
NIOSH 7304 Elements (incl. Pt) by ICP (Microwave digestion)	PVC 5.0 µm	Cassette 1 – 4 l/min	ICP-AES	9 µg/sample	67
IPA Harmonised Methodology for the Sampling of Pt in Workplace Atmospheres	MCE 0.8 µm	IOM sampler 2 l/min	ICP-MS	0.00008 µg per sample or 0.0027 µg/m^3 (30 l air sample)	64,66

LOD – Limit of Detection; MDHS – Methods for Determination of Hazardous Substances; NIOSH – National Institute for Occupational Safety and Health; OSHA – Occupational Safety and Health Administration; MCE – Mixed Cellulose Ester; PVC – Poly Vinyl Chloride; AAS-GF – Graphite Furnace Atomic Absorption Spectrometry; ICP-MS – Inductively Coupled Plasma-Mass Spectrometry; ICP-AES – Inductively Coupled Plasma-Atomic Emission Spectroscopy; HSE – Health and Safety Executive; IPA - International Platinum Group Metals Association; IOM – Institute for Occupational Medicine; a IOM inhalable sampler, multi orifice inhalable sampler or conical inhalable sampler may be used.

Table 3. Summary of countries/organizations that classify soluble Pt as sensitizers

Country/Organization	Type of sensitizing notation			Reference
	Respiratory	Skin	Not specific	
United Kingdom	X	-	-	[72]
South Africa	X	-	-	[73,74]
Sweden	-	-	X	[75]
Canada (British Colombia)	-	-	X	[76]
Australia	-	-	X	[77]
Germany	X	X	-	[78]
Japan	X	X	-	[71]


a.
Ref
Cat
C & R
MC
Soluble Pt (µg/m3)
OEL
8
23
15
203
135
438
373
463
8
26
*
7
a. Maynard et al., 1997
b. Vos et al.,2012 (Production)
c. Vos et al.,2012 (Engineering)
d. Heederik et al., 2016 (Refinery 1)
e. Heederik et al., 2016 (Refinery 2)
f. Heederik et al., 2016 (Refinery 3)
g. Heederik et al., 2016 (Refinery 4)
h. Heederik et al., 2016 (Refinery 5)
i. Maynard et al., 1997
j. Petrucci et al., 2005
k. Cristaudo et al.,2007
l. Maynard et al., 1997

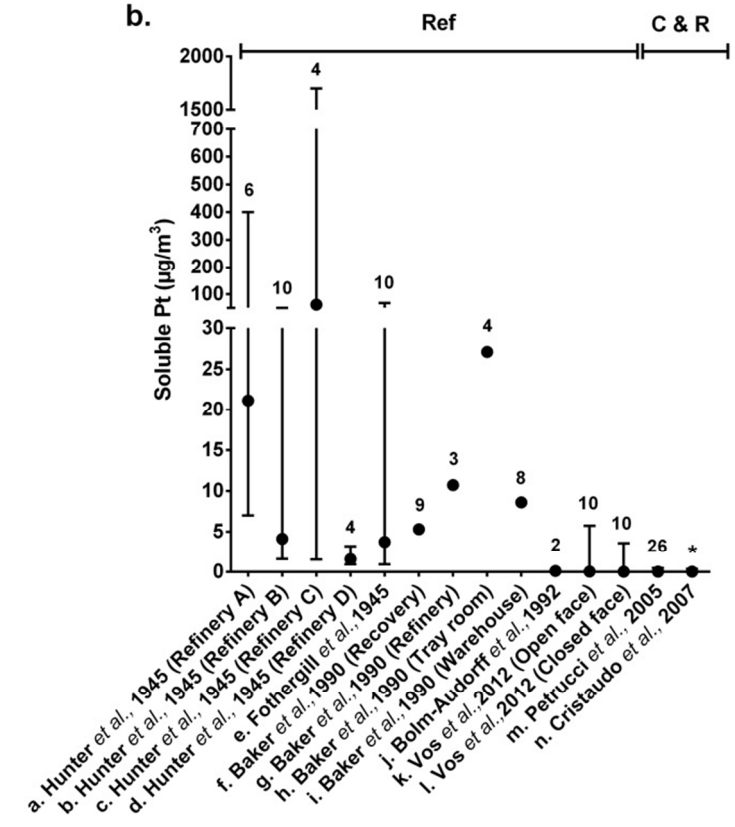

b.
Ref
C & R
Soluble Pt (µg/m3)
6
10
4
4
10
9
3
4
8
2
10
10
26
*
a. Hunter et al., 1945 (Refinery A)
b. Hunter et al., 1945 (Refinery B)
c. Hunter et al., 1945 (Refinery C)
d. Hunter et al., 1945 (Refinery D)
e. Fothergill et al., 1945
f. Baker et al., 1990 (Recovery)
g. Baker et al., 1990 (Refinery)
h. Baker et al., 1990 (Tray room)
i. Baker et al.,1990 (Warehouse)
j. Bolm-Audorff et al., 1992
k. Vos et al.,2012 (Open face)
l. Vos et al.,2012 (Closed face)
m. Petrucci et al., 2005
n. Cristaudo et al., 2007

Figure 1. Chronological summary of studies reporting personal exposure to soluble Pt in various industries (Figure 1a) as well as area measurements of soluble Pt (Figure 1b) in different industries. The number of measurements collected during each study is indicated above each plot. * indicates that the number of measurements was not indicated in the study. ● indicates the geometric mean concentration. The upper and lower limits of the plots indicate the maximum and minimum values, respectively. The industries where the measurements were collected are indicated above the graph: Ref – Refineries; Cat – Catalysts production plants; C & R – Catalyst production and recycling plants; MC – Metal coating plants. Note that Baker et al.[33] (Figure 1b) only reported the geometric means of results from different areas of the refinery without reporting minimum and maximum values. For Petrucci et al.[53] and Cristaudo et al.[6] the mean percentage soluble fraction reported in the total airborne area samples for each work area was used to estimate the soluble Pt concentration of the personal measurements where only the total Pt concentrations in the total airborne fractions were reported.