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Characterisation of nickel industry workplace aerosols by particle size and nickel species

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WORLD HEALTH ORGANISATION
COLLABORATING CENTRE
FOR OCCUPATIONAL HEALTH

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The aim of this project was to collect data on nickel aerosol chemical speciation and particle size distribution in two large-scale nickel production facilities. Personal and fixed point samples were collected to assess airborne dust concentrations, nickel concentrations, nickel speciation and aerosol particle size distributions using IOM and Marple cascade impactor sampling heads.

A total of 46 (30 personal and 16 static) inhalable samples and 28 (18 personal and 10 static) cascade impactor samples were obtained. All samples were analysed gravimetrically; the static inhalable samples were analysed for nickel species, whilst the remaining samples were analysed for total nickel.

Inhalable dust and nickel concentrations were below the relevant UK Workplace Exposure Limits, although some high exposure levels were observed in the raw materials area of Site One and conversion and furnace areas of Site Two. In the raw materials and electrolysis areas of Site One and the furnace area in Site Two, the vast majority of the dust concentration consisted of particles greater than 10µm. At Site Two there was evidence in the rotary kilns area of a greater proportion of finer particles being present. Although nickel speciation analysis was undertaken and reported, management at both Sites have raised concerns regarding their validity, in particular the sulfidic nickel species results, when considering the composition of the raw materials used and the final products.

The findings of this research program will inform the risk assessment process for nickel exposure in this industry.

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1 INTRODUCTION

The Human Health part of the EU Nickel Risk Assessment is in the final stages of completion. The EU Risk Assessment Reports for nickel and nickel products (e.g., DEPA, 2005(a); DEPA, 2005 (b)), have identified certain workplace scenarios where risk reduction strategies may have to be developed. However, these conclusions are based on default assumptions about the nickel species involved, their particle size and the associated exposure levels. The aim of this project was to collect more data on chemical speciation and particle size distribution to enable more informed decisions to be made within the nickel risk assessment process.

There is evidence that different nickel species have different toxicities. Chemical speciation of workplace aerosol can be performed by sequential dissolution and analysis of nickel salts from occupational hygiene samples. Alternatively, an indication of nickel species can be obtained from a determination of total nickel versus soluble nickel concentrations or the determination of total nickel versus soluble, sulfidic, metallic and oxidic nickel concentrations.

Aerosol size distribution affects the inhalability and subsequent regional deposition of particles in the lung. The particle size distribution is clearly important when assessing risks to health and when comparing exposure data. Generally there is a lack of data on particle size distributions for typical nickel production and use scenarios.

Also, there is lack of knowledge on how particle size distributions from workplace aerosols compare to particle size distributions from aerosols used in animal experiments to assess toxicity of nickel aerosols. Particle size distributions from laboratory-generated aerosols used in animal experiments appear to be different from particle size distributions in workplace aerosols. The laboratory-generated aerosols contain considerably more particles in the finer size fractions (2-3 µm aerodynamic particle diameter).

This report describes the measurement strategy, methods and analytical techniques used and discusses the results in context with the workplace conditions observed at the production site.

The Danish Environmental Protection Agency have published a proposition for the Human Health Risk Reduction Strategy (RRS) for nickel and nickel compounds (Danish Environmental Protection Agency, 2006). This RRS document aims (among other scopes) to set a Community binding Occupational Exposure Limit (OEL) under the Carcinogens Directive (EC, 2004). In response to the publication of the RRS, which followed the completion of the two sampling campaigns, the present research will inform the development of suitable sampling methods for any future EU wide occupational exposure limit.

2 AIMS

The study was intended to supplement existing scientific knowledge about nickel aerosol exposure within primary nickel production industries.

The final aims of this project were as follows:

a) To collect personal inhalable dust measurements to determine the inhalable dust and total nickel concentrations.
b) To collect fixed-point, static inhalable dust measurements to determine the inhalable dust concentrations and determine the nickel species composition for each of the collected samples.
c) Collect personal and static samples to assess the particle size distributions for both dust and nickel aerosols.

The survey was carried out at two large-scale nickel production facilities and several workplace processes were included at each site.

3 WORKPLACE DESCRIPTIONS

The following section describes the normal and observed workplace conditions and working practices for the two production sites included in this survey.

3.1 SITE ONE

3.1.1 Overview of Site One

This site manufactures high purity electrolytic nickel (13,000 tons /year), crystallized nickel chloride and nickel chloride in solution (3,000 tons /year) using a hydrometallurgical process. The plant operates continuously for eleven months of the year, with production shutting down during the month of July for scheduled maintenance activities. The majority of the plant operates on a three 8-hour shift system, these being 05.00-13.00; 13.00-21.00 and 21.00-05.00, with certain areas of the plant operating on two shifts (05.00-13.00; 13.00-21.00). Approximately 180 people in total are employed at the site.

Several key processes are undertaken and the site was divided into four discrete sections, which are described in the following sections. The first three, which are listed below, are collectively known as the *chemical processes*:

1. Raw materials reception, grinding & leaching
2. Purification & electrolysis
3. Nickel chloride process

The last section is known as the *metallic process* and includes cathode stripping, nickel cutting and packing.

3.1.2 Raw materials reception, grinding & leaching

Nickel matte is delivered to the site by road in closed containers (operated by external contractors). The amount of nickel matte delivered is dependent on production requirements although it is estimated that approximately 50 tonne is delivered per day (over two to three deliveries). The nickel matte is stored in stockpiles in an indoor warehouse, with the truck driver wearing a 3M dust mask with an in-built P3 (high-efficiency particle) filter during off-loading. No other personnel are in this area when the nickel matte is unloaded.

The off-loaded nickel matte is transferred to loading silos using a mechanical caterpillar loader. The loader has a closed, pressurized, cabin with filtered air supply (outside filter replaced monthly) and the driver does not normally come in contact with the raw materials. This individual normally works in this area for half a shift (either morning or afternoon), four days a week, spending 15 minute periods inside the warehouse, every half hour or so.

The nickel matte is crushed in the raw materials reception area by two crushers. The crushed material is then transferred to a set of reactors for leaching by chlorine in the presence of ferric chloride. The raw material grinding and transfer process is fully automatic and one operator per shift carries out periodic checks on the process. A P3, high efficiency, dust mask must be worn by the operator when working in this area.

The warehouse is cleaned once a fortnight by an external contractor. The cleaning is performed using a centralized vacuum cleaner with a continuous control of the rejected dust.

The nickel leaching process is carried out by sparging the nickel matte suspension with chlorine gas. This causes the nickel, cobalt and iron to be leached into solution and converted to metal chlorides, whilst the sulphur remains in the elemental state. The operator responsible for checking the grinding process also carries out periodic checks and sampling of the leaching process, both of the mixed materials and final leaching product. Sampling is usually carried out every 2 hours and normally takes around 10-15 minutes. The solution of nickel, cobalt and iron chlorides is filtered to remove sulphur and other insolubles. The filtered solution is then transferred to the extraction and purification process.

3.1.3 Purification & electrolysis

Essentially there are two main purification stages. Iron is firstly extracted, using a selective organic solvent (tributyl phosphate), in a bank of mixer-settlers functioning on the counter-current principle. Next, the cobalt is extracted from the iron-free solution of nickel and cobalt chlorides by mixer-settlers, using a different solvent (tri-isooctylamine). This yields a solution of pure cobalt chloride and a cobalt-free solution of nickel chloride.

The high purity nickel chloride solution is pumped to storage vessels. The leaching and purification processes are automatic and the process conditions are monitored and controlled from a remote control room by one operator. A second operator moves between the units to obtain samples to confirm the process is running correctly.

The nickel chloride solution then moves directly to either the nickel chloride area for crystallization or to the electrolysis process to produce metallic nickel.

For the latter process, the nickel chloride solution is pumped to electrolysis tanks. The electrolysis process liberates chlorine gas at the anode so a very high standard of control is applied to the tank emissions. This chlorine is recycled for the leaching process. Upon removal the cathodes are washed in an acid bath before moving onto the metallic process (see Section 3.1.5).

There was no noticeable odour of chlorine gas and little evidence of liquid spillage from the tanks. There are two operators in the electrolysis area who inspect, lift and rinse the finished nickel cathodes. They spend the remaining time (50% of their shift) supervising the process from inside a control room. There is also one crane operator. All the cathode handling tasks are done by mechanical methods and the workers wear PVC coated protective gloves and overalls. There is no requirement for respiratory protection to be worn during normal operations in the electrolysis area.

3.1.4 Nickel chloride process

These processes take place in a separate building. Nickel chloride is sold by the plant both in solution and crystal form. The solution is sold in bulk (guaranteed composition of >176g/l nickel) and delivered by road tanker.

Purified nickel chloride is converted to nickel chloride hexahydrate crystals (guaranteed composition >24% nickel) by an automatic, enclosed process. The crystals are stored in high

level silos and are transferred to the packing station via a weigh cell that measures out the correct quantity of material to be packed. The crystals are dispensed into 25 kg woven-polypropylene bags lined with moisture-proof polyethylene within the enclosed packing machine. This process is highly automated, with usually only one operator per shift monitoring the equipment, supervising the crystallization process and moving stock around the plant by fork-lift truck. The filled bags are manually stacked onto pallets or into 1 tonne capacity cardboard boxes. Other operators may help with packing and stacking depending on production requirements.

3.1.5 Metallic processes

High-purity electrolytic nickel is produced, with a guaranteed composition of no less than 99.97 % nickel. Two areas of the plant are concerned with the high purity nickel, these being the cathode stripping area and the cutting and packing area, with 2 employees working in each of the two areas per shift. The supervisor of both areas moves between these to ensure that activities run smoothly. A forklift truck driver also operates between the two areas, moving the stripped cathodes to the cutting area.

Cathode Stripping

Nickel metal sheets are stripped from the cathodes. The cathodes are subjected to heat treatment. Once cooled the sheets are transferred to the cutting and packing area.

Cutting and Packing

Prior to dispatch, the cathodes are cut on automatic shearing machines, either being supplied in squares (100x100 mm or 50x50 mm). This work takes place in a large, airy warehouse where little dust was observed.

The cathodes are transported to the area by forklift truck and placed onto the shearing machine by a robotic system. One operator supervises the cutting process.

The squares are packed on automated lines into 250 or 300 kg steel drums (observed packing of 250kg drums) which are loaded on pallets (6 drums per pallet). A second operator is responsible for checking the weight of these drums, removing or adding nickel squares so that the required weight is achieved. These drums are sealed and stored in the area for dispatch.

The operators wear gloves (to protect against cuts), overalls, ear protection and safety boots.

3.2 SITE TWO

3.2.1 Overview of Site Two

The second site manufactures ferronickel (nickel content of 18-23%) using oxidized ores (laterites) obtained from local mines. The plant operates continuously throughout the year. Operators work on three 8-hour shifts; 06.00-14.00; 14.00-22.00 and 22.00-06.00. Approximately 490 people are employed at the site, with the vast majority of these (392) being skilled workers.

Several key processes are required for ferronickel production including raw material handling, rotary kilns, smelting (using electric arc furnaces), conversion and granulation. These are discussed in the following sections.

3.2.2 Raw materials handling, rotary kilns

Ore from the local laterite nickel mines and other raw materials, including lignite and coal, are transported to the site via trucks or ship by contract staff. The raw materials are transferred to storage areas or silos. Bulldozers, loaders and trucks as well as conveyers are used. The vehicles are fitted with closed cabins without air conditioning, although it was noticed that operators often left their cabin doors open during their work.

The various raw materials are transferred from their respective storage silos to the Rotary Kilns via dose-metric conveyor belts. Mixing is not a continuous process but takes place every half hour, with operators adjusting the conveyors from a control room to ensure that the correct mix of materials is achieved. Approximately 8,000 tons of raw materials are mixed per day.

Three or four operators are involved in the mixing process per shift. They work predominantly from a control room located next to the conveyor systems. The operators periodically leave the control room to inspect the conveyors to ensure the smooth running of the process and deal with any blockages etc. Face-masks (type not established) are available and although the wearing of these is mandatory, no operators were observed wearing them.

The mixed product is transferred to the feeding silos of the rotary kilns where it is dried, heated and reduced. The four rotary kilns are fitted with a terminal gas cleaning system. The calcined material is collected in bins for further transport. The interim product of this process stage is pre-reduced Fe/Ni, which is loaded into bins, from where these are moved by a crane over the electric arc furnaces for unloading. Final turnout of material is approximately 7,000 tons calcined product per day, whereby the losses compared to raw material account for drying and combustion.

In total, 10-12 operators work in the rotary kilns area per shift, working predominately from nearby control rooms. They also periodically move around the general work area as part of their supervisory and maintenance responsibilities, with the wearing of face masks being variable. Water sprays were reported to be used around the rotary kilns on dry days to suppress general dust levels.

3.2.3 Smelting / furnace area

Calcine, the rotary kiln intermediate product, is loaded from the top into electric arc furnaces (there are five on site) for smelting. Soderberg electrodes are lowered into the furnace for the melting of the material. The temperature in the electric arc furnaces is approximately 1,400°C.

Each of the five furnaces requires four operators per day, with approximately 25 individuals working in the entire furnace area, undertaking a variety of tasks. The four crane operators per day located at the top of the units, in closed filtered cabins with air at positive pressure, move the pots between the ERFs. Ten operators per shift tap slag and molten metal from the furnaces. Metal tapping of the furnace into 50-ton transport pots occurs 3-5 times per shift, with the metal then being transported to the conversion area where the ferronickel is refined. The resulting slag represents approximately 85% of the input material (7,000 tons per day). This slag is granulated by flushing seawater, and is then dumped to a designated area of the sea through barges (permit granted by local government). Four operators in the morning shift

add paste to the Soderberg electrodes. The remaining operators help supervise loading/unloading tasks or operate the furnaces from nearby control rooms.

3.2.4 Refining and granulation

The alloy is refined and enriched in the OBM converters. Molten metal tapped from the electric arc furnaces is transferred to one of the 2 OBM-type convertors in pots (only one convertor is in operation at any one time), after which oxygen is blown through the liquid metal phase.

The molten metal is then granulated by pouring it into a water bath. Ferronickel particles (>3 mm diameter) precipitate and are removed as the final product. Fine material that is also generated is recycled to the OBM converters. Four heats per shift are treated in the converters, with 250 tons of ferronickel being produced each day, equating to 8,000 tons per month. This is transported to clients in bulk.

Three operators are responsible for operating the cranes and 3-4 operators for the granulation process. There are also 1-2 foremen in this area, with other individuals involved in assisting and supervising the various processes.

3.2.5 Additional comments

Most operations are carried out under general ventilation, with no specific additional ventilation or (local) extraction measures available. Operators were noted to move around work areas frequently throughout their work shift, with the rest of their working time spent in well-ventilated cabs or control rooms. Workers move directly to their operation area without previously reporting to a central facility and have a 20-30 minute break per shift, which is taken in nearby control rooms; there is a canteen and designated rest facilities.

4 METHODS

4.1 SAMPLING

Personal and fixed point (static) samples were collected to assess airborne dust concentrations, nickel concentrations and aerosol particle size distributions. The measurements and related exposure information are summarised in Table 1.

Table 1: Types of samples to be collected and primary sample analysis outcome

Sampling apparatus	Inhalable dust conc.	Total nickel conc.	Nickel speciation	Particle size distribution
Personal IOM sampler	X	X		
Static IOM sampler	X		X	
Cascade impactor (personal & static)				X

Note: As a secondary outcome of the nickel speciation analysis, total nickel for the static IOM samplers can be determined. As a secondary outcome of the cascade impactor substrates analysis total dust and nickel can be determined.

Personal airborne dust sampling was carried out using sampling apparatus in accordance with Health and Safety Executive method MDHS 14/3 (HSE, 2000). This involved using an IOM inhalable dust sampler loaded with a pre-weighed cassette containing a 25mm quartz fibre filter. The filters were then analysed gravimetrically in the laboratory for airborne dust (Section 4.3.1) and total nickel content concentrations (Section 4.3.3).

Fixed point sampling using IOM sampling heads was also used to determine the background inhalable dust levels and also levels of nickel species in the working environment (Section 4.3.4). It was assumed that there are no differences in chemical speciation from the fixed point samplers and the personal samples (Vincent *et al*., 1995).

The aerosol size characteristics of the airborne dust were determined using Marple multi-stage personal cascade impactors (Thermo Electron Corporation, SE298), either being worn by the operator or positioned as a static sampler within the working environment.

The "entry" for the standard Marple sampler as supplied by the manufacturer, does not meet the criteria for an inhalable dust sampler (CEN, 1993) and would result in an under-estimation of the size fraction of the larger airborne particles (approximately 20 µm and above). We therefore modified these devices to have an inlet designed to collect inhalable dust fraction in accordance with the inhalable dust convention (CEN, 1993). Characterising aerosols using cascade impactors with the inlet modification has been undertaken in similar projects by the IOM (Hughson, 2005).

The Marple cascade impactors contain 8 collection stages, the physical dimensions of which are standard sizes. The sampled air enters the inlet of the sampler and accelerates through the slots in the first impactor stage. Particles larger than the cut-off point of the first stage impact onto the collection substrate. The air-stream flows through the narrower slots in the second stage and subsequent stages and the particles impact onto the respective collection substrates. By measuring the mass of dust collected on each stage, the size distribution of the airborne dust can be determined. The cut-off points for the eight stages of this impactor are 21.3 µm

and above, 14.8, 9.8, 6.0, 3.5, 1.55, 0.93, 0.52 µm and the final filter, which collected all remaining particles. The cut-off points are defined as the impactor stages through which 50% of the particles off the specified aerodynamic diameter will pass.

Mylar polyester collection substrates were used in the cascade impactors. These were pre-greased in order to prevent sample losses due to particle bounce effects, and were pre-weighed in the IOM laboratory prior to use. After use, the cascade impactors were dismantled and the exposed collection media removed and placed into labelled containers. The component parts were cleaned and then reassembled on-site with fresh pre-weighed Mylar substrates installed. All exposed collection media were re-weighed in the IOM laboratory to enable the size distribution analysis to be completed (Section 4.3.1). These media were subsequently analysed to determine their total nickel content (Section 4.3.3).

The samplers were each connected to a battery operated sampling pump using Tygon tubing and the flow rate was set at 2.0 l/min (+/- 5%) using a calibrated rotameter. All samples were allocated a unique sample number and clearly labelled.

For personal samples, the pump was secured to the operator by attaching to a belt worn around the waist. The sampling head was clipped to the lapel of the overalls, within the breathing zone, i.e. within 200mm of the nose and mouth. Once the pump and sampling head were attached satisfactorily, the pump was switched on and the time recorded. The flow rate was checked every 2-3 hours. If small deviations from the set flow rate were noted, the pump was adjusted up or down to obtain the required reading and the deviation was ignored. If the flow rate deviated by more than 5% of the set value, the sample was rejected. At the end of the sampling period, the pump was switched off and the time and flow rate was noted. The samples were transported in labelled containers back to the laboratory for subsequent analysis.

The sampling procedures for the static background measurements were otherwise the same as that for the personal sampling, with the exception that the samples were left in the fixed position for a representative period of the working shift.

For every ten IOM and cascade impactors samples collected, one IOM filter cassette, cascade impactor substrate and back-up PVC filter were set aside as field blank samples. These were handled in the same way as the other field samples except that they were not exposed to workplace air. Samples were blank corrected.

All primary data including sampling times, operators' name, company name and work area were recorded in a sample record form developed specifically for the study. This enabled samples to be collected, packed, transferred and analysed in a controlled and systematic manner.

Samples of bulk materials were collected from each of the following 3 areas at Site Two – ore mixing, rotary kilns and the conversion/granulation area. For each sample collected, at least 1 gram of dust was deposited into a labelled Sterlin sample tube. These was then placed into individual zip-lock bags and stored separately from the personal and static samples collected.

4.2 SAMPLING STRATEGIES

Initial site visits were undertaken at two primary nickel production sites. The purpose of these visits was to identify specific areas of the production site to target for the sampling campaign. Sampling strategies were devised and agreed upon by Institute of Occupational Medicine (IOM), European nickel Industry Association (ENIA) and the site management of the production sites. Tables 2 and 3 detail the number of proposed personal and static samples to be collected at Sites One and Two, respectively. The surveys were carried out during November and December 2006.

Operators involved in normal production activities in each of the identified areas were included in the surveys. Operators from each of the production areas were identified by the site management to participate in the sampling campaign. Samples were collected over a representative portion of the working shift whenever possible. The static samplers were positioned in areas with high aerosol levels so that a sufficient mass of dust could be collected to allow nickel speciation analysis (ideally a mass of 1mg should be collected). Where possible, the static samplers were positioned away from obstructions, fresh inlets or strong winds, with the exact positioning of the device being determined on the day of sampling and with due consideration of the plant activities.

Table 2: Proposed sampling strategy for Site One

Production area	No. of samples			
	Personal samples		Static samples	
	IOM	Cascade	IOM	Cascade
Raw materials, grinding & leaching	7	7	1	1
Purification & electrolysis	6	6	1	1
Nickel chloride packing	6	6	1	1
Metallic processes	5	5	1	1
TOTAL	**24**	**24**	**4**	**4**

Table 3: Proposed sampling strategy for Site Two

Production area	No. of samples			
	Personal samples		Static samples	
	IOM	Cascade	IOM	Cascade
Raw materials	4	4	2	2
Rotary kilns	4	4	2	2
Furnaces (smelting)	8	8	2	2
Conversion & granulation	8	8	2	2
TOTAL	**24**	**24**	**8**	**8**

4.3 LABORATORY ANALYSIS

4.3.1 Gravimetric analysis

The filter cassettes from the IOM inhalable dust samplers were analysed gravimetrically as outlined by MDHS 14/3 (HSE, 2000). The results were expressed in terms milligrams of inhalable dust per cubic metre of air of (mg/m^3).

The Mylar substrates and PVC back-up filters from the personal cascade impactors were prepared according to the manufacturer's instructions and were analysed by gravimetrically.

The sample masses for each set of cascade impactor collection substrates were entered into a computer spreadsheet and a mathematical algorithm used to calculate the percentage mass of dust within each size range (Hughson, personal communication).

4.3.2 Method validation for greased Mylar substrates total nickel analysis

Prepared greased Mylar substrates were analysed to check the compatibility of the sampling medium with the laboratory reagents and analytical equipment. Ten greased substrates were analysed to determine blank nickel levels and to establish the detection limit for the analytical method.

The analytical recovery was determined by preparing a number of spike samples using 100% nickel metal powder, with the spiked substrates being left overnight to stabilise. These were then acid digested and analysed using the method detailed in section 4.3.3.

4.3.3 Total nickel analysis

Due to the presence of nickel oxides being identified during the X-ray diffraction analysis (XRD) analysis (see Section 4.3.4), it was decided to use a modification of the Zatka *et al* (1992) digestion method, with the total nickel content being determined using inductively coupled plasma atomic emission spectroscopy (ICP/AES) in accordance with a documented in-house method, based on OSHA method 121 (OSHA, 1991).

Following gravimetric analysis of the personal IOM samplers, the quartz fibre filters were transferred to Teflon beakers. Hydrofluoric (HF) acid (5ml) and nitric acid (5ml) were added and the sample heated to dissolve the filter. Perchloric acid (5ml) was then added and the sample heated to produce heavy fumes (max temp 280^0C). The sample was cooled and the sides of the beaker washed down with distilled water then placed on the hotplate and heated to produce heavy fumes. The rinse and evaporation was then repeated in excess perchloric acid to remove all HF. The digestion was continued until all the perchloric acid had volatilized, the resulting warm residue was dissolved in 1ml of 50% hydrochloric acid and made up to 10mls with distilled water.

The cascade impactor substrates were transferred to beakers, with 5ml of nitric acid being added. The beakers were covered with a watch glass and heated on a hotplate until the filter disintegrated (the cascade impactor substrates don't completely dissolve but do break up leaving a residue in the beaker). Perchloric acid (4ml) was then added and the samples heated to 210-240^{o}C until the perchloric acid fumed and volatilised. 1ml of 50% HCl was then added to the warm residue, with the solution then being filtered and made up to 10ml using distilled water.

4.3.4 Nickel speciation analysis

The static IOM cassettes were reweighed to determine the inhalable dust concentration and the samples were shipped to an independent laboratory nominated by the sponsor for analysis

of nickel species. Prior to shipping, the static samples collected at Site Two were analysed, along with the bulk samples, using X-ray diffraction (XRD) techniques.

4.3.4.1 X-ray diffraction (XRD) analysis

XRD techniques were used to provide a qualitative assessment of the nickel species presented in the samples. A portion of each bulk sample was finely ground to create a sample of uniform particle size. These were scanned qualitatively using routine XRD techniques. The resultant diffractions patterns were then compared with standard reference materials and search-match indices to determine qualitatively the nickel species present. The identification of the nickel species in the bulk samples was based on matching at least two peaks for the relevant compound. These provided a reference for the static background samples.

The IOM filters were analysed as per the bulk samples. The identification of the nickel species in some of the filter samples was based on the presence of a single peak. It should be noted that this would not normally be sufficient information to allow identification however knowledge of the species present in the bulk samples allowed an assessment to be made.

4.3.4.2 Leaching method

The Zatka *et al* (1992) 'wet-chemical procedure' provides a means to analyse soluble, sulfidic, metallic and oxidic compounds of nickel. This method was originally developed to analyse the species present in operations where sulfidic ores were processed. The sample was leached in the following sequence, using increasingly stronger solutions. Examples of nickel compounds which may be present at the various leached phases are also provided:

1. soluble nickel using 0.1M ammonium citrate (e.g. normal salts – sulphate, chloride);
2. sulfidic nickel using a peroxide – citrate solution (e.g. sulfides, arsenides, selenide, telluride);
3. metallic nickel using a bromine-methanol solution (e.g. nickel, nickel alloys and steels) and finally;
4. oxidic nickel using nitric-perchloric acids (hydrofluoric acid may also be added) (eg nickel oxide, complex oxides, silicates).

Each stage selectively dissolves a number of related nickel species, with each leach solution and the insoluble residue from the third leach being analysed for nickel by atomic absorption spectrometry (AAS).

4.4 DATA ANALYSIS

The airborne dust and nickel concentrations for the various process areas and sites were summarised in terms of maximum, minimum, arithmetic mean, median and 90th percentile values, although median and 90th percentile values were not calculated in instances where three or less samples were collected. In order to summarise exposure data properly, it was necessary to adjust data values that were below the limit of detection. For sample results below the limit of detection (LOD), the exposure values were set to a level of half the LOD, in accordance with the approach suggested by Rajan-Sithamparanadarajah *et al.,* (2004).

The cascade impactor raw data were reviewed using the following criteria:

1. Is there useful information in terms of total dust and nickel mass to determine particle size distributions? Samples where the majority of the stages were less than the LOD were not considered for determining particle size distributions further.

2. Assessment of dust fractions (coarse or fine). The respirable fraction of the total dust and nickel can be approximated by determining the cumulative percentage mass of aerosol obtained at the cascade impactor Stages 4 and below (aerodynamic diameter less than 6μm).

3. Graphic display of cumulative size distribution on linear and logarithmic scale by plotting the cumulative percentage mass of aerosol obtained at the various cascade impactor stages (for those data sets where aerosol and /or nickel distributions were decided could be sensibly obtained).

There were a number of instances where both the IOM and cascade impactor sampling heads were paired, either on a person or as fixed point measurements. The relationship between the IOM and cascade impactor sampling heads was investigated by regression analysis using SPSS for Windows v14.0. This was done for inhalable dust and total nickel concentrations. Differences between the regression lines for personal and static nickel samples were investigated using the techniques of regression in groups and analysis of covariance (Armitage and Berry, 1994). In order for the assumptions of regression analysis to be fulfilled, measurements were transformed using natural logs prior to analysis.

5 RESULTS

5.1 COLLECTED SAMPLES

5.1.1 Sampling survey at Site One

Table 4 details the number of proposed and actual personal samples collected during the sampling campaign in November 2006 whereas Table 5 provides details of the number of static samples proposed and subsequently collected.

Several issues were encountered which influenced the number of samples collected. Due to problems with the courier the equipment was not delivered on time, resulting in the campaign being restricted to two rather than three days. Upon delivery of the sampling equipment it was found that the vast majority of the greased substrates used in the cascade impactors were stuck to their sample tins, most likely due to being turned over during transit, and so were rendered unusable. Due to personnel limitations sampling was restricted to between 07.00 and 18.00 on each day of sampling (which meant that the duration pf personal sampling was limited on each of the two shifts covered) and to no more than four employees per shift.

Table 4: Personal sampling – proposed and actual sampling strategy at Site One

Production area	No. of IOM/cascade impactor samplers			
	Proposed		Actual	
	IOM	Cascade	IOM	Cascade
Raw materials, grinding & leaching	7	7	2	2[1]
Purification & electrolysis	6	6	4[1]	1
Nickel chloride packing	6	6	4	1
Metallic processes	5	5	-	-
TOTAL (excluding those that failed)	**24**	**24**	**9**	**3**

[1] one sample failed

Table 5: Static sampling – location of fixed samplers at Site One

Production area	No. of IOM/cascade impactor samplers			
	Proposed		Actual	
	IOM	Cascade	IOM	Cascade
Raw materials, grinding & leaching	1	1	5[1]	2
Purification & electrolysis	1	1	2	1
Nickel chloride packing	1	1	3	2[2]
Metallic processes	1	1	2[2]	1
TOTAL (excluding those that failed)	**4**	**4**	**9**[3]	**4**

[1] one sample failed
[2] all failed
[3] two samples were transferred to the NIPERA repository for storage and future analysis.

Overall, 9 IOM personal samples (median sampling duration 208 min, range 185-242 min), and 3 cascade impactor personal samples were collected (median 195 min, range 175-445). Nine IOM static samples were collected, although two were transferred to the NIPERA repository for future sample analysis, leaving seven remaining for analysis within this project

(median 451 min, range 193-548 min). Four static cascade impactors were also obtained (median 432.5 min, range 271-548 min).

5.1.2 Sampling survey at Site Two

Table 6 details the number of proposed and actual personal samples collected during the sampling campaign in November – December 2006 whereas Table 7 provides details of the number of static samples proposed and subsequently collected.

The sampling campaign was carried out over three days. Slightly fewer cascade impactor samples were collected than originally hoped. Despite taking extra precautions to ensure that the greased substrates did not become stuck to the tins during transportation, many were still rejected due to this. Six cascade samples also failed during the sampling period. With regards to the inhalable dust sampling, all 24 personal and 9 static samples were collected over the three days however the flow rates of three personals samples deviated by greater than 5% and were therefore discarded.

Table 6: Personal sampling – proposed and actual sampling strategy at Site Two

Production area	No. of IOM/cascade impactor samplers			
	Proposed		Actual	
	IOM	Cascade	IOM	Cascade
Raw materials	4	4	4	4
Rotary kilns	4	4	4[1]	2
Furnaces (smelting)	8	8	8[1]	8[2]
Conversion and granulation	8	8	8[1]	7[3]
TOTAL (excluding those that failed)	**24**	**24**	**21**	**15**

Notes:
*For smelting area, only one crane operator was available at the time and fewer tapping operators were sampled due to safety concerns and problems with attaching sampling equipment to protective clothing.
[1] one sample failed
[2] two samples failed
[3] four samples failed

Table 7: Static sampling – location of fixed samplers at Site Two

Production area	No. of IOM/cascade impactor samplers			
	Proposed		Actual	
	IOM	Cascade	IOM	Cascade
Raw materials	2	2	1*	1*
Rotary kilns	2	2	2	2
Furnaces (smelting)	2	2	2	2
Conversion & granulation	2	2	4	1
TOTAL (excluding those that failed)	**8**	**8**	**9**	**6**

*only one set was collected as at the time the static sampling was undertaken in this area a strike was taking place which resulted in the feed belt to the other rotary kilns being stopped.

In total, 21 personal (median 260 min, range 211-339 min) and 9 static samples were obtained (median 280 min, range 165-303 min) using IOM sampling heads; 15 personal (median 237

min, range 211-335 min) and six static cascade impactor samples (median 293 min, range 268-303 min) were also collected.

5.2 METHOD VALIDATION FOR MYLAR SUBSTRATES TOTAL NICKEL ANALYSIS

The LOD for the analytical method was determined to be 0.2µg.

The analytical recovery of nickel from the greased substrates using the modified digestion method was tested using spike levels. The results of this procedure are detailed in Table 8.

Table 8: Results of analytical recovery tests at four different sample spike levels

Spike Ni (µg/ml)	Actual Ni recovered (µg/ml)	% Recovery efficiency
0.090	0.121	133.8
0.090	0.082	91.0
0.090	0.079	87.6
Average		**104.1**
0.294	0.246	83.5
0.294	0.237	80.3
0.294	0.243	82.5
Average		**82.1**
1.802	1.957	108.6
1.802	1.543	85.6
1.802	1.587	88.0
Average		**94.1**
3.154	3.586	113.7
3.154	3.046	96.6
3.154	2.822	89.5
Average		**99.9**
Overall % recovery efficiency		**95.1**

This analysis showed an average recovery efficiency of 95% over the range of four spike levels. No adjustment has been made to the site measurements to account for recovery.

5.3 INHALABLE DUST AND NICKEL LEVELS USING IOM SAMPLING HEADS

A total of 30 personal IOM samples were collected from both sites (9 from Site One; 21 from Site Two) and these were analysed gravimetrically to determine inhalable dust concentrations. The inhalable dust samples were subsequently analysed for total nickel. A total of 15 static IOM samples were collected from both sites (7 from Site One; 9 from Site Two) and these were analysed gravimetrically to determine inhalable dust concentrations. The inhalable dust samples were subsequently analysed for nickel speciation by an external laboratory (Section 5.4).

Table 9 provides summary statistics of the personal and static total inhalable dust and nickel levels for the main production areas of the two sites. All results for the inhalable dust and total nickel levels from the IOM samples are provided in Appendix 1.

Table 9: Summary results of IOM sampling head inhalable dust and nickel concentrations by production area

Area	N	Inhalable dust conc. (mg/m^3)				Total Ni conc. (µg/m^3)			
		Min	Max	Median	90th %	Min	Max	Median	90th %
Site One – personal samples									
Raw materials	2	0.7	1.5			8.7	178.0		
Electrolysis	3	0.5	9.1			2.4	814.9		
Nickel chloride	4	0.5	0.8			1.8	46.7		
Overall	**9**	**0.5**	**9.1**	**0.7**	**3.0**	**1.8**	**814.9**	**24.6**	**301.36**
Site One – static samples									
Raw materials	4	0.3	5.7			92.0	2481.6		
Electrolysis	1	0.3	0.3			19.8	19.8		
Nickel chloride	2	0.2	0.4			22.5	66.5		
Overall	**7**	**0.2**	**5.7**	**0.4**	**3.2**	**19.8**	**2481.6**	**92.0**	**1292.62**
Site Two – personal samples									
Raw materials	4	2.0	4.2			0.7	20.3		
Rotary kilns	3	1.6	9.3			0.2	15.2		
Furnace	7	2.2	25.2			8.7	170.7		
Conversion/granulations	7	1.2	13.1			2.8	101.9		
Overall	**21**	**1.2**	**25.2**	**3.8**	**9.3**	**0.2**	**170.7**	**15.2**	**54.35**
Site Two – static samples									
Raw materials	1	1.5	1.5			36.6	36.6		
Rotary kilns	2	1.8	3.0			59.0	91.3		
Furnace	2	8.3	12.0			106.3	127.9		
Conversion/granulations	4	2.4	14.3			72.6	203.4		
Overall	**9**	**1.5**	**14.3**	**2.9**	**12.5**	**36.6**	**203.4**	**91.3**	**143.01**

For Site One, airborne concentrations of personal inhalable dust ranged from 0.5 to 9.1 mg/m^3, with corresponding total nickel levels ranging from 1.8 to 814.9 µg/m^3. Airborne concentrations for the static samples ranged from 0.2 to 5.7 mg/m^3, with corresponding total nickel levels ranging from 19.8 to 2481.6 µg/m^3. The highest personal inhalable dust and nickel exposure levels were obtained for an electrolysis operator (9.1 mg/m^3), with the second highest exposures being obtained for a raw materials operator (inhalable dust 1.5 mg/m^3 and nickel 178.0µg/m^3). All the other personal total inhalable exposure levels were below 1.0 mg/m^3 and total nickel levels below 50 µg/m^3. The 90th percentile for the personal inhalable dust and nickel exposures was 3.0 mg/m^3 and 301.4 µg/m^3, respectively (i.e. 90 percent of the samples had an exposure concentration less than or equal to this value), with the 90th percentiles for the static samples for Site One being 3.2 mg/m^3 and 1292.6 µg/m^3. The highest static inhalable dust and nickel exposures were observed in the raw materials storage area though this does include measurements collected during routine cleaning activities. It is important to note that the nickel content of the dust at Site One was generally less than 10% of the dust which emphasises the importance of direct nickel measurements rather than using gravimetric estimates of exposure.

For Site Two, airborne concentrations of personal inhalable dust ranged from 1.2 to 25.2 mg/m^3, with corresponding total nickel levels ranging from 0.2 to 170.7 µg/m^3. Airborne concentrations for the static samples ranged from 1.5 to 14.3 mg/m^3, with corresponding total

nickel levels ranging from 36.55 to 203.43 µg/m^3. The highest personal inhalable dust and nickel exposure levels were obtained for a furnace operator, with the highest static dust and nickel exposures being in the conversion / granulation area. The 90th percentile for the personal inhalable dust and nickel exposures was 9.3 mg/m^3 and 54.4 µg/m^3 and static exposures 12.5 mg/m^3 and 143.0 µg/m^3. The nickel content of the dust at Site Two was approximately less than 1%. The lower content of nickel of the dust at Site Two compared to Site One is consistent with the different nature of the starting process materials at these sites (laterite ore containing ~1% nickel at Site Two versus concentrate containing 75% nickel at Site One).

5.4 RESULTS OF AIRBORNE PARTICLE SIZE ANALYSIS

Table 10 provides summary statistics for the cascade impactor data for the main production areas of the two sites. Raw data for the cascade impactor dust and nickel analysis are included in Appendix 2. Summaries of the airborne dust and nickel concentrations obtained from the individual cascade impactors are provided in Appendix 3.

For Site One, the static cascade impactor concentrations ranged from 0.2 to 4.3 mg/m^3 for total dust and 1.1 to 1,259.2 µg/m^3 for total nickel, with the highest concentrations being observed in the nickel matte (raw materials) area. The personal cascade impactor concentrations ranged from 0.8 to 3.3 mg/m3 for total dust and 5.5 to 275.1 µg/m^3 for total nickel, with the highest personal concentrations also being observed for an operator working in the raw materials area.

For Site Two, the cascade impactor results ranged from 0.4 to 31.6 mg/m^3 and 1.6 to 184.9 µg/m^3 for total dust and total nickel, respectively, with the highest concentrations (for both personal and static samples) being observed in the furnace area.

For Site One it is difficult to compare the personal and static cascade impactor results given that few measurements were collected. Higher dust and nickel concentrations were obtained for the personal samples in the raw materials and electrolysis areas. For Site Two a greater number of personal and static cascade impactor samples were collected. Both the personal and static samplers demonstrated high exposure levels to both total dust and nickel in the furnace area. Relatively high personal and static dust and nickel levels were also observed in the rotary kilns area. In most areas the summary results for the static samples were generally higher than those obtained from the personal samples. This may be due to the fact that most operators only worked periodically in the immediate work environment, spending the rest of their work shift in a nearby control room.

Table 10: Summary results of cascade impactor dust and nickel concentrations by production process

Area	N	Inhalable dust conc. (mg/m^3)				Total nickel conc. ($\mu g/m^3$)			
		Min	Max	Median	90th %	Min	Max	Median	90th %
Site One - personal samples									
Raw materials	1	3.26	3.26	-	-	275.08	275.08	-	-
Electrolysis	1	0.75	0.75	-	-	5.48	5.48	-	-
Nickel chloride	1	1.24	1.24	-	-	8.81	8.81	-	-
Overall	**3**	**0.75**	**3.26**	**-**	**-**	**5.48**	**275.08**	**-**	**-**
Site One - static samples									
Raw materials	2	0.62	4.31	-	-	232.41	1259.15	-	-
Electrolysis	1	0.21	0.21	-	-	1.09	1.09	-	-
Nickel chloride	0	-	-	-	-	-	-	-	-
Nickel cutting	1	0.36	0.36	-	-	7.82	7.82	-	-
Overall	**4**	**0.21**	**4.31**	**0.49**	**3.20**	**1.09**	**1259.15**	**120.12**	**951.13**
Site Two - personal samples									
Raw materials	4	0.52	4.18	-	-	6.01	49.78	-	-
Rotary kilns	2	0.71	3.11	-	-	2.29	14.66	-	-
Furnace	6	1.17	31.63	-	-	6.28	184.85	-	-
Conversion/granulations	3	0.40	0.74	-	-	1.61	3.88	-	-
Overall	**15**	**0.40**	**31.63**	**1.58**	**6.19**	**1.61**	**184.85**	**9.62**	**46.35**
Site Two - static samples									
Raw materials	1	0.46	0.46	-	-	2.93	2.93	-	-
Rotary kilns	2	0.92	1.54	-	-	9.68	20.10	-	-
Furnace	2	6.95	16.93	-	-	34.56	108.17	-	-
Conversion/granulations	1	0.76	0.76	-	-	5.43	5.43	-	-
Overall	**6**	**0.46**	**16.93**	**1.23**	**11.94**	**2.93**	**108.17**	**14.89**	**71.37**

Note: values reported are the sum of the values measured at each of the stages present in each sampler

In several instances it was possible to compare results from static and personal measurements. Details of the airborne dust and nickel concentrations obtained from the cascade impactor and the corresponding measurements from the IOM samplers are provided in Table 11 for comparison.

Table 11: Comparison of inhalable dust and nickel measurements obtained by paired combination of cascade impactors and IOM inhalable dust samplers

Sample type	Work area/activity	Dust conc. (mg/m3)		Nickel conc. (µg/m^3)	
		IOM sampler	Cascade Impactor	IOM sampler	Cascade Impactor
Site One					
Personal	Nickel chloride packing	0.8	1.2	46.67	8.81
Static	Raw materials	5.7	4.3	2481.6	1259.15
Static	Electrolysis	0.2	0.2	19.8	1.09
Static	Raw materials	1.1	0.6	401.8	232.41
Site Two					
Personal	Raw materials	2.9	1.6	7.6	10.33
Personal	Raw materials	2.0	0.5	0.7	6.01
Personal	Rotary kilns	1.6	0.7	0.2	2.29
Personal	Raw materials	4.2	4.2	20.3	49.78
Personal	Raw materials	3.2	2.0	2.0	7.17
Personal	Furnace	4.7	7.1	25.7	38.34
Personal	Furnace	3.8	1.2	17.0	6.28
Personal	Furnace	4.0	2.2	21.9	16.36
Personal	Furnace	4.6	2.5	31.5	17.23
Personal	Furnace	25.2	31.6	170.7	184.85
Personal	Conversion/granulation	3.8	0.5	6.7	3.88
Personal	Granulation	1.2	0.4	12.5	1.61
Personal	Granulation	1.9	0.7	2.8	3.22
Static	Rotary kilns	3.0	1.5	59.0	20.10
Static	Raw materials	1.5	0.5	36.6	2.93
Static	Rotary kilns	1.8	0.9	91.3	9.68
Static	Furnace	8.3	7.0	106.3	34.56
Static	Rotary kilns	12.0	16.9	127.9	108.17
Static	Conversion	2.4	0.8	99.8	5.43

Note: For IOM samplers, the values are direct measurements while for the cascade impactors, the sum of the values measured at each of the stages are reported. Different digestion & analytical methods were used to determine total nickel concentrations.

The IOM inhalable dust sampler may be considered to be the reference sampler, since the sampling efficiency has been validated against the inhalable dust criteria (HSE, 2000). The cascade impactor does not have the same capability to retain all of the sampled dust and may be expected to produce an underestimate of exposure due to internal wall losses. The data in Table 11 shows differences between the pairs of samplers, which may be explained by the inherent differences between the two samplers.

The relationship between inhalable dust measured using the IOM sampling head and the cascade impactor is shown in Figure 1. The line illustrating the ideal relationship between the two sampling methods is shown and it is apparent that in general higher results were obtained

from the IOM sampling head compared with corresponding values recorded by the cascade impactor.

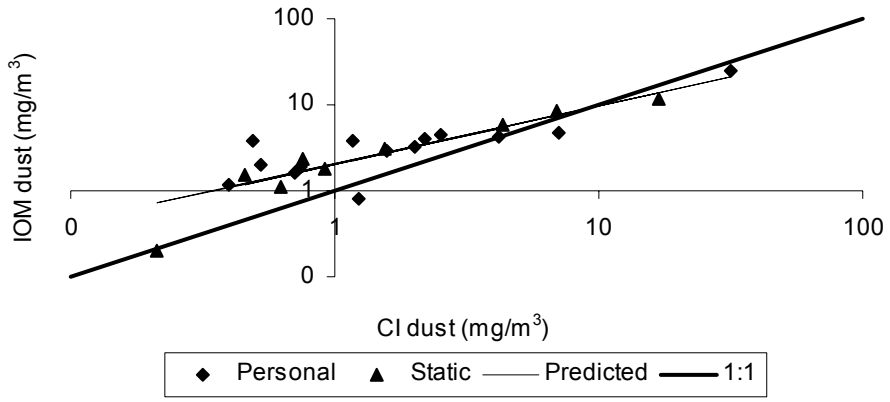

Figure 1 Comparison of IOM sampling head and cascade impactor for inhalable dust

A correlation of 0.87 between the two sampling methods was obtained. The linear relationship (on the log scale) between the methods is also illustrated on the graph and the relationship is:

$$\text{Ln IOM} = 0.68 \times \text{Ln CI} + 0.71$$

The slope and intercept were highly significant ($p<0.001$) and the relationship was not modified by sample measurement type (personal / static).

The relationship between total nickel measured using the IOM sampling head and total nickel using the cascade impactor is shown in Figure 2. It is apparent the relationship between the two samplers is very different for personal samples compared with static samples and therefore separate regression lines were fitted. The line illustrating the ideal relationship between the two sampling methods is also shown. It can be seen that whereas personal measurements obtained from the IOM sampling head are similar to the corresponding personal values recorded by the cascade impactor, static measurements from the IOM sampling head are higher than the corresponding static values from the cascade impactor. A correlation of 0.69 and 0.93 between the two sampling methods was obtained for the personal and static samples respectively.

The linear relationship (on the log scale) between the methods is also illustrated on the graph and is:

$$\text{Ln IOM} = 0.93 \times \text{Ln Ci} + 0.07 \text{ (personal)}$$

$$\text{Ln IOM} = 0.58 \times \text{Ln CI} + 2.91 \text{ (static)}$$

The slopes for both the personal and static samples were highly significant ($p=0.007$ and $p<0.001$). The intercept for the personal samples was not significant ($p=0.925$), but was highly significant for the static samples ($p<0.001$).

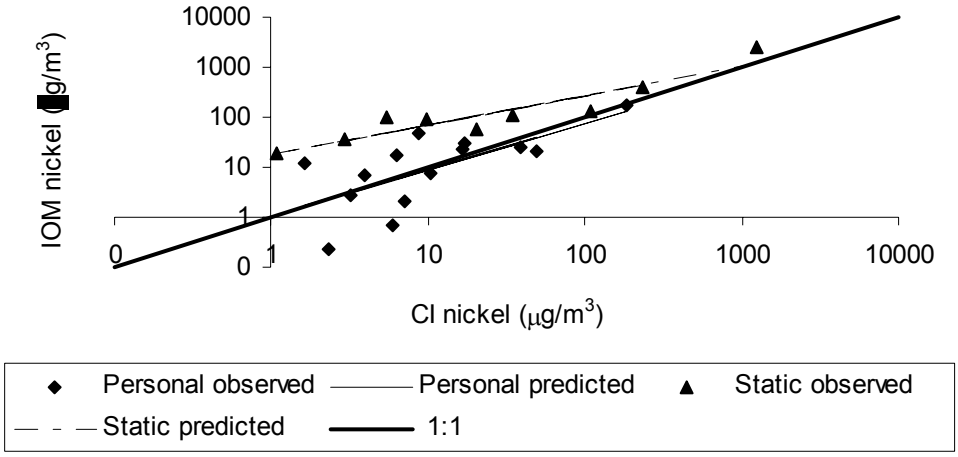

Figure 2 Comparison of IOM sampling head and cascade impactor for total nickel

The raw cascade impactor data were first assessed to determine their usability for determining size distribution for inhalable dust and nickel (Table 12). Table 12 also provides details of the total percentage of dust / nickel present at the impactor stages 4 and below (<6µm) as an approximation of the respirable dust faction.

Particle size distributions at Site One are limited but they show pretty consistent results, with the 'respirable' nickel fraction (composition less than aerodynamic diameter cut-off point of 6µm) ranging from 11-26.5% of the overall nickel, with the majority of the dust and nickel data being above the aerodynamic diameter cut-off point of 6µm.

The personal and static samples collected in the furnace area of Site Two demonstrate fairly good agreement with the vast majority of the total dust and nickel aerosol being coarse (being above the aerodynamic diameter cut-off point of 6µm). However there was some evidence in the rotary kilns area of a greater proportion of finer particles (<6µm cut-off point) being present.

Table 12 Expert opinion on the usability of each cascade impactor data set

Sample code	Description	Distribution able to be obtained? Dust	Ni	% mass total dust stage 4 and below	% mass total nickel stage 4 and below	Comments
Site One						
CI/01/02	Personal electrolysis	N	N	61.4	47.4	Distributions not possible. <LOD for most stages.
CI/01/03	Personal caterpillar cab	Y	Y	57.5	10.5	Ni mostly 'coarse' particles
CI/01/04	Static Nickel cutting	N	Y	46.3	22.0	Dust mass <LOD except stage 1 Ni mostly 'coarse' particles
CI/01/05	Static Raw materials	Y	Y	17.5	10.7	Both dust and Ni mostly 'coarse' particles
CI/01/07	Personal $NiCl_2$ packing	N	Y	26.0	26.5	Dust mass <LOD except stage 4 Ni mostly 'coarse' particles
CI/01/09	Static Electrolysis	N	N	55.6	41.7	Distributions not possible. <LOD for most stages.
CI/01/10	Static Raw materials	Y	Y	31.0	23.5	Both dust and Ni mostly 'coarse' particles
Site Two						
CI/02/01	Personal Rotary kilns	N	N	40.3	50.0	Distributions not possible. <LOD for most stages.
CI/02/02	Personal Raw materials	Y	Y	26.7	40.9	Possible bimodal distribution for Ni' and 'coarse' component
CI/02/03	Personal Rotary kilns	Y	Y	20.1	17.6	Both dust and Ni mostly 'coarse' particles
CI/02/04	Personal Raw materials	Y	Y	25.2	42.3	Bimodal distribution, 'fine' and 'coarse' component
CI/02/05	Personal Raw materials	Y	Y	13.5	39.4	Both dust and Ni mostly 'coarse' particles
CI/02/06	Personal Raw materials	N	N	55.6	26.9	Distributions not possible. <LOD for most stages.
CI/02/07	Static Rotary kilns	Y	N	38.9	57.0	Dust mostly 'coarse' particles. Ni difficult to interpret
CI/02/08	Static Raw materials	N	N	44.6	38.9	Distributions not possible. <LOD for most stages.
CI/02/09	Static Rotary kilns	Y	Y	33.6	63.8	Ni mostly 'fine' particles, 'coarse' dropped out
CI/02/12	Personal Furnaces	N	Y	23.6	34.8	Skewed towards coarse; some pick up of fines.
CI/02/13	Personal Furnace crane	N	N	29.6	41.4	Both dust and Ni mostly 'coarse' particles
CI/02/14	Personal Furnaces	N	N	22.5	48.9	Both dust and Ni mostly 'coarse' particles
CI/02/15	Personal Furnaces	Y	Y	3.9	15.7	Both dust and Ni mostly 'coarse' particles
CI/02/16	Personal Furnaces	Y	Y	14.6	35.0	Both dust and Ni mostly 'coarse' particles
CI/02/17	Personal Furnaces	Y	Y	5.4	12.3	Both dust and Ni mostly 'coarse' particles

Sample code	Description	Distribution able to be obtained? Dust	Ni	% mass total dust stage 4 and below	% mass total nickel stage 4 and below	Comments
CI/02/18	Static Loading furnaces	Y	Y	2.8	25.2	Both dust and Ni mostly 'coarse' particles
CI/02/19	Static Conversion	N	N	32.1	50.0	Distributions not possible. <LOD for most stages.
CI/02/20	Static Metal tapping	Y	Y	4.8	20.0	Both dust and Ni mostly 'coarse' particles
CI/02/22	Personal Granulation	N	N	41.3	45.0	Distributions not possible. <LOD for most stages.
CI/02/23	Personal Conversion / granulation.	N	N	48.5	38.5	Distributions not possible. <LOD for most stages.
CI/02/27	Personal Granulation	N	N	60.0	50.0	Distributions not possible. <LOD for most stages.

The results of those cascade impactors where the total nickel airborne particle size analysis were deemed to provide reasonable distributions are illustrated in Figures 3 to 8. These show the percentage (Y-axis) of the workplace aerosol having less than a particular aerodynamic diameter (X-axis) in micrometres (μm). Figures 3-8 illustrate these data using a linear and a logarithmic scale (to enable the lower particle sizes to be clearly illustrated). Graphs illustrating data where the total dust airborne particle size was able to be determined are provided in Appendix 4.

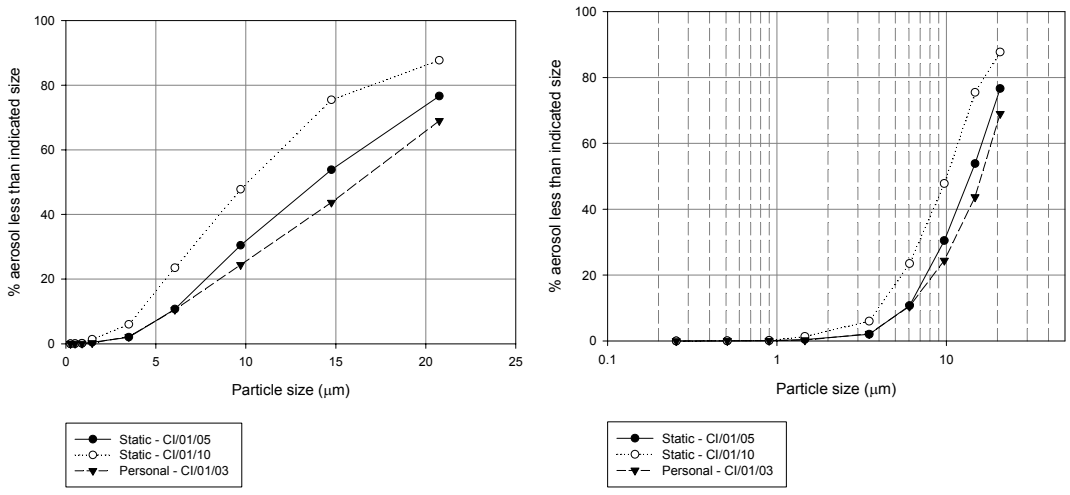

Figure 3 Raw materials (Site One) Aerosol size distributions (total nickel) assessed by cascade impactors (linear scale left and log scale right)

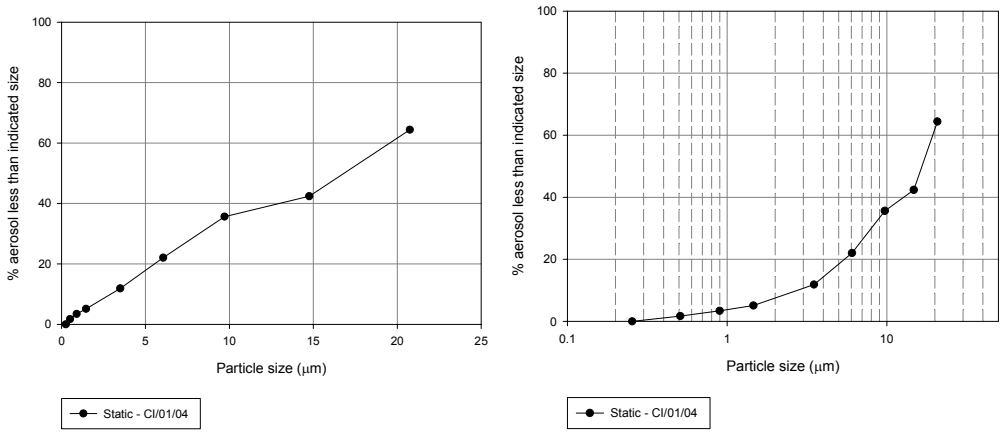

Figure 4 Nickel cutting (Site One) Aerosol size distributions (total nickel) assessed by cascade impactors (linear scale left and log scale right)

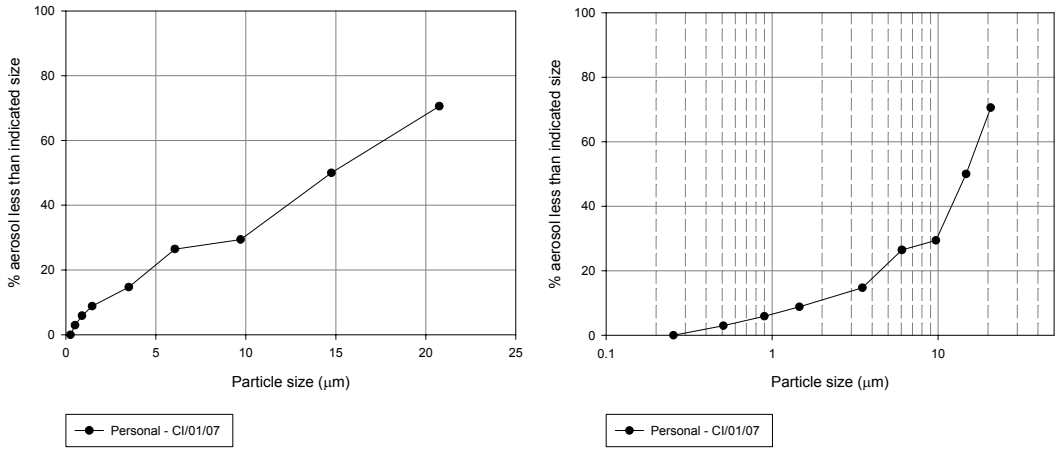

Figure 5 Nickel chloride packing (Site One) Aerosol size distributions (total nickel) assessed by cascade impactors (linear scale left and log scale right)

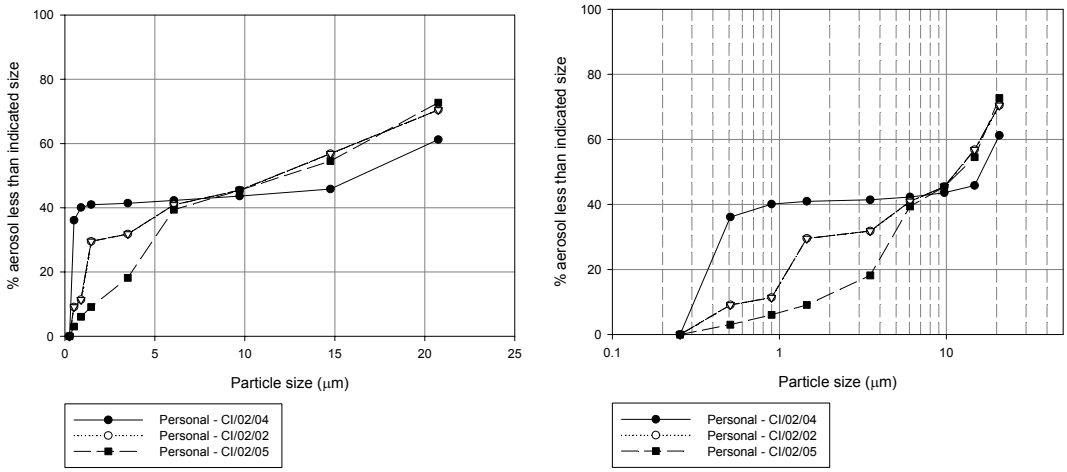

Figure 6 Raw materials (Site Two) Aerosol size distributions (total nickel) assessed by cascade impactors (linear scale left and log scale right)

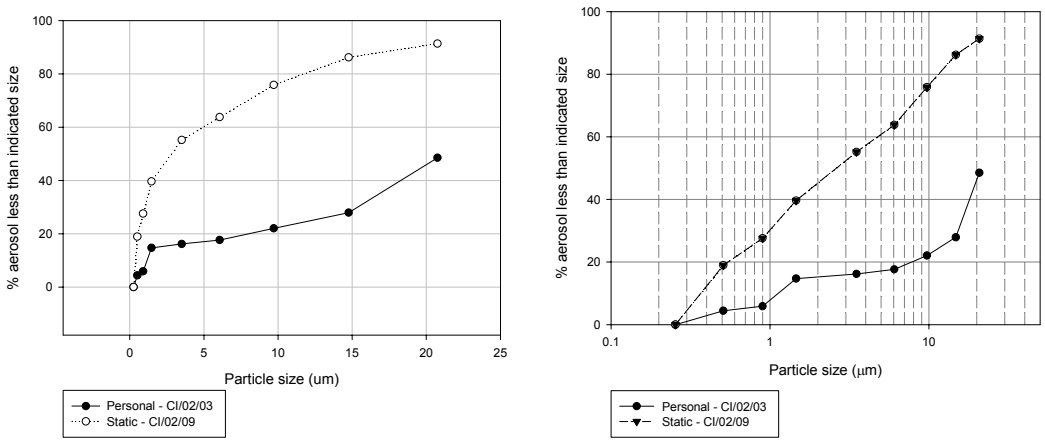

Figure 7 Rotary kilns (Site Two) Aerosol size distributions (total nickel) assessed by cascade impactors (linear scale left and log scale right)

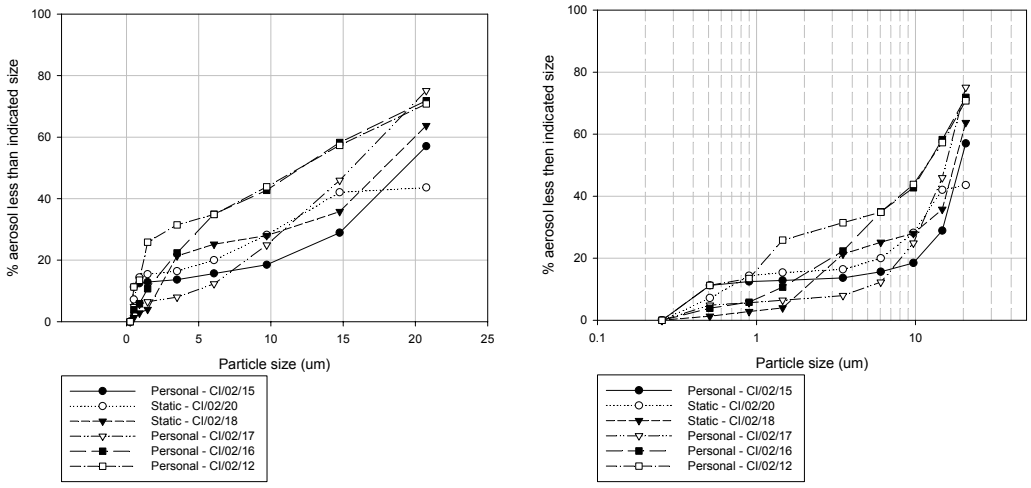

Figure 8 Furnace (Site Two) Aerosol size distributions (total nickel) assessed by cascade impactors (linear scale left and log scale right)

5.5 RESULTS OF NICKEL SPECIATION ANALYSIS

Tables 13 and 14 show the results of the nickel speciation analysis using the Zatka *et al* (1992) method for the static samples collected at Sites One and Two, respectively. At Site One, nickel speciation analysis was undertaken using the Zatka *et al* (1992) whilst for sample collected at Site Two, both XRD and the leaching methods were used. Table 15 shows the results of the XRD sample analysis for the bulk samples collected at Site Two which helped informed the qualitative XRD analysis. Nickel iron oxide was detected in all five bulk samples and nickel oxide in three. These components were also detected in one form or another in all except two of the static aerosol samples analysed by XRD. Analysis of the static samples using the Zatka *et al* (1992) method also revealed that nickel oxide species were the most prominent throughout the Site:

- 31.0% in the raw materials area (based on one sample, with there also being a high presence of soluble (31.9%) and sulphide (28.7%) nickel species in this area);
- 76.9-84.6% in the rotary kilns area;
- 62.3-75.8% in the furnace area;
- 73.1 – 76.6% in the conversion area and;
- 46.4 – 53.2% in the granulation area.

Greater composition of 'soluble' nickel species and 'sulfidic' nickel was also observed in the granulation area. The percentage of metallic nickel particles was low, ranging from 3.5-8.3%.

At Site One, in the nickel matte area, sulfidic nickel was the most prominent nickel species, ranging from 53.0-81.2% of the total nickel composition of the aerosol, with soluble nickel species being the next prominent species (12.6 – 25.3%). In the electrolysis area (based on one sample), nickel oxides and soluble nickel species were the most common, composing of 39.6 and 27.6% of the total nickel content, respectively. In the nickel chloride packing area, soluble nickel species were the most common (30-43.8%), with oxidic nickel and sulphidic nickel species also being well represented.

Table 13: Nickel speciation results for static samples collected at Site One

Sample ID	Location	Mass nickel species (µg)					Species composition of total nickel (%)			
		Soluble	**Sulfide**	**Metallic**	**Oxide**	**TOTAL**	**Soluble**	**Sulfide**	**Metallic**	**Oxide**
QF0036	Raw materials	170	1094	53	28	1345	12.6	81.3	3.9	2.1
QF0042	Nickel chloride packing	16	9.4	2.5	8.6	36.5	43.8	25.8	6.8	23.6
QF0043	Raw materials caterpillar	21	44	3	15	83	25.3	53.0	3.6	18.1
QF0052	Raw materials	69	276	39	13	397	17.4	69.5	9.8	3.3
QF0054	Nickel chloride packing	7	4.9	5.1	6.3	23.3	30.0	21.0	21.9	27.0
QF0056	Electrolysis	6	3.1	4	8.6	21.7	27.6	14.3	18.4	39.6
QF0058	Raw materials	35	130	11	17	193	18.1	67.4	5.7	8.8

Table 14: Nickel speciation results for static samples collected at Site Two

Sample ID	Location	Mass nickel species (µg)					Species composition of total nickel (%)				XRD analysis
		Soluble	**Sulfide**	**Metallic**	**Oxide**	**TOTAL**	**Soluble**	**Sulfide**	**Metallic**	**Oxide**	
QF0088	Rotary kiln	3.6	3.2	1.6	28	36.4	9.9	8.8	4.4	76.9	Ni Iron Oxide Ni Oxide
QF0092	Raw materials	6.9	6.2	1.8	6.7	21.6	31.9	28.7	8.3	31.0	Ni Silicon
QF0098	Rotary kilns	2.9	3.6	1.9	46	54.4	5.3	6.6	3.5	84.6	Ni Iron Oxide
QF0087	Metal tapping area	3.3	4	1.3	27	35.6	9.3	11.2	3.7	75.8	Ni Iron Oxide Ni Silicon
QF0090	Furnace area	16	8	2.6	44	70.6	22.7	11.3	3.7	62.3	Ni Iron Oxide
QF0104	Conversion area	6	4	2.2	40	52.2	11.5	7.7	4.2	76.6	Ni Iron Oxide Ni Oxide Ni Sulphide
QF0086	Granulation area	6.1	14	2.8	26	48.9	12.5	28.6	5.7	53.2	Ni Silicon
QF0082	Conversion area	12	8.8	3.1	65	88.9	13.5	9.9	3.5	73.1	Ni Iron Oxide Ni Oxide
QF0113	Granulation area	7.1	7.3	1.8	14	30.2	23.5	24.2	6.0	46.4	Ni Sulphide Ni Oxide

Table 15: Results of XRD analysis for bulk samples collected at Site Two

Sample	Area sample collected	Nickel species detected
1	Near mouth of rotary kiln	Nickel Iron Oxide, Nickel Oxide, Nickel Silicon
2	After passing through venturi scrubber system of rotary kiln	Nickel Iron Oxide
3	After passing through multicyclone of rotary kiln, just before electrostatic scrubber	Nickel Iron Oxide, Nickel Oxide, Nickel Silicon
4	Near control room where rotary kiln process ends and materials moved to furnace area	Nickel Iron Oxide, Nickel Silicon
5	Output of conversion dust collection system	Nickel Iron Oxide, Nickel Oxide, Nickel Sulphide

Management at both Sites have raised concerns regarding the nickel speciation results, which are discussed in Section 6.3.

6 DISCUSSION

6.1 INTRODUCTION

This report describes results of two exposure measurement surveys in the nickel industry and provides unique data on size distribution and nickel speciation. Information on size distributon and nickel speciation is of importance as these factors are likely to affect the risk of workers exposed in these workplaces. Unfortunately, a number of difficulties were encountered during the measurement surveys which has reduced the number of samples available for analyses and which may have affected how representative the results are, particularly for Site One.

6.2 INHALABLE DUST AND NICKEL CONCENTRATIONS

The UK long-term workplace exposure limits for inhalable dust is 10 mg/m^3 and for nickel and its inorganic compounds (except nickel carbonyl) is 0.1 mg/m^3 for water soluble nickel compounds and 0.5 mg/m^{3}for nickel and water-insoluble nickel compounds (HSE, 2005).

At Site One, inhalable dust levels were generally very low compared to the UK inhalable dust exposure limit, with only two samples (one personal – electrolysis operator; one static – raw materials area) being greater than 1.6 mg/m^3. The total nickel levels were generally below the UK nickel and water-insoluble nickel compounds limit except for all the static samples collected in the raw materials area (ranging from 0.40-2.48 mg/m^3) and one personal sample collected from an electrolysis worker (0.81 mg/m^3). The highest personal exposure of 9.1 mg/m^3 for inhalable dust and 814 µg/m^3 for total nickel were observed for an electrolysis worker. Given the nature of the tasks undertaken in this area, the result being far in excess of other personal and static sample results for this area and also those previously reported for electrolysis workers by Hughson (2005) and duplicated in Table 16, it is felt that this result should be viewed with caution. It was also noted that the nickel content of the dust at Site One was approximately no higher than 10% of the total dust which emphasises the importance of direct nickel measurements rather than using gravimetric estimates of exposure.

Table 16: Results of previous air monitoring undertaken at Site One for electrolysis workers (Hughson, 2005)

	Airborne concentration (mg/m3)	
	Inhalable dust	**Inhalable nickel**
Electrolysis – unloading/cleaning	0.8	0.01
Electrolysis – lifting / checking	0.6	0.02
Electrolysis – lifting / checking	1.4	0.01

Cleaning and maintenance activities were undertaken in many of the areas and hence results may not always be indicative of normal working conditions, although they do give an insight of likely exposures during such activities. Given the nature of the work processes, conditions and control measures in place it is felt that exposures at this site on the whole would be low except for the raw materials area. Exposures were highest in the raw materials area on the day when normal activities were undertaken (static sample – inhalable dust 5.7 mg/m^3; nickel 2481.6 µg/m^3). Although exposures were higher in this area, the use of respiratory protection when present in this area was mandatory and the caterpillar cabin was well ventilated.

At Site Two, inhalable dust levels were higher, with two personal and two static measurements being in excess of the UK limit (convertor operator and furnace operator and static samples in these two areas) and two personal samples being just below the limit (rotary kilns and furnace operators). Total nickel exposures were all very low and well below the UK nickel and water-

insoluble nickel compounds limits. Total nickel represents a very small proportion of the total dust composition, accounting on average throughout the whole site for about 0.5% of the total dust. The lower nickel content of the dust is consistent with the nature of the starting process materials at these sites, these being laterite ore containing approximately 1% nickel. It should be considered that the sampling campaign was undertaken during the cooler, damper months and it is possible that exposures may be greater in the summer months when conditions are drier, windy and greater chance of dust becoming airborne.

6.3 NICKEL SPECIATION ANALYSIS

Two methods were used to identify the nickel species present in the static aerosols samples collected, these being X-Ray Diffraction (XRD) and the Zatka *et al* (1992) method. The use of XRD analysis has been reported in other studies investigating speciation of airborne dust from nickel primary production plants (for example, Anderson *et al.,* 1999). XRD analysis provides a qualitative assessment of the main components of a sample, with the limiting factors being the amount of substances present and the fact that many compounds can share primary peak positions (Clark S, personal communication). In theory, XRD can detect all crystalline nickel compounds providing that a sufficient sample is collected.

The Zatka *et al.* (1992) method is perhaps the most commonly used nickel speciation method, being used for over 20 years. This leaching method applies increasingly strong acidic solutions to the sample and with subsequent measurement of the dissolved fraction by atomic absorption spectrometry (or plasma emission methods). This method was specifically developed to speciate compounds encountered during the refining of sulfidic nickel ores.

As reported in section 5.5, at Site One, sulfidic nickel was reported as being the most prominent nickel species in the nickel matte area; nickel oxides and soluble nickel species being the most common in the electrolysis area whereas in the nickel chloride packing area, soluble nickel species were the most common, with oxidic nickel and sulphidic nickel species also being well represented. Hughson (2005) also noted that sulfides were the most dominant nickel species in the raw materials (matte storage) handling area, with soluble nickel being the most prominent of the four species in the nickel chloride packing area. As nickel chloride hexahydrate is considered to be highly soluble this finding is not unexpected.

Management at Site One have raised concerns regarding the speciation results, which are based on a limited number of static samples, in particular with reference to the presence and levels of sulfidic and oxidic nickel species present. For example, Site One has reported that in the nickel chloride packaging area, the standard material manufactured contains 0.02% S whereas the purest nickel chloride materials produced contain a mean 0.003% S. Previous monitoring data undertaken by the Site reported the highest sulfidic levels to be 0.11% of total nickel in 2006 during the production of standard material, whilst 20% was reported during this sampling campaign (based on two sample results). In the electrolysis area oxidic species were also reported (based on one sample result) however the Site states that their presence is not expected.

It has been reported that there is the possibility of cross contamination between the nickel species. Leakage of the extraction reagent may result in incomplete dissolution of the component of interest. The net effect of this would be less nickel extracted at that particularly stage, with more nickel being left behind to be incorrectly measured as part of the next species to be extracted (Luk *et al.,* 2000). It has also been noted that a nickel species can become completely entrapped in a non-leachable phase and is prevented from reacting with the selected leachant, which in turn results in under reporting for that stage and over-reporting in the subsequent stage when the compound is eventually released (ENIA, personal communication). The finding that approximately 20% of total nickel was sulphidic in the nickel chloride

packaging area of Site One could possibly be an example of this analytical error and may be caused by some partially hydrated nickel chloride crystals not dissolving fully at the first leaching stage. It is possible that incomplete dissolution at earlier stages has occurred during the sample analysis which may have impacted on the results although it is not possible to confirm that this is indeed the case..

Particle size can also play a big role in determining the fraction in which various nickel compounds will dissolve (ENIA, personal communication). For example, the leaching of very fine particles in a given leaching stage may be different than relatively larger particles of the same species. Knowledge of the particle size distribution can therefore be used to help interpret any possible biases of the leaching method.

XRD analysis was undertaken on the static samples collected at Site Two with the results of this analysis, in terms of primary peaks identified, closely matching the results provided by the quantitative Zatka *et al* (1992) method. Vincent *et al* (2001) estimated the costs of a single speciation analysis to be in the region of US $200 which is thought to be far in excess of a single XRD analysis. Use of the XRD analysis on the static samples before commencing the total nickel analysis on the personal samples was of value given that the analysis identified the presence of nickel oxides. Had these not be identified the original OSHA digestion method would have been employed (OSHA, 1991) which could potentially have resulted in an underestimation of the samples total nickel content due to poor digestion of the oxide species present.

Given the high level of agreement of the XRD and subsequent quantitative speciation analysis it is felt that XRD is useful at providing a qualitative indicator of the main nickel species present in the workplace environment. However XRD cannot be relied upon to identify all the nickel species which may be present in the aerosols. For example, the more soluble nickel species at Site Two were not always identified with XRD although they were identified using the Zatka *et al* (1992) speciation analysis. In order to adequately identify the more minor species components and provide a quantification of the nickel species present, the Zatka *et al* (1992) or a suitable adaptation or modification of this method such as that prescribed by Luk *et al* (2000) may be necessary.

The results of the nickel speciation analysis at Site Two suggested that nickel oxide species dominated throughout the site, particularly in the rotary kilns, furnace and conversion areas. In the raw materials sulfidic and soluble nickel species were also reported to be present in high levels. High fractions of oxidic nickel are expected during refining and conversions processes. Low fractions of soluble nickel species at this site are perhaps not unexpected given the nature of the production processes employed. Management at Site Two has also raised concerns regarding the speciation results, in particular with reference to the presence of sulfidic species. Site personnel report that the raw materials used contains a maximum of 0.2% sulfides, with the final product containing 0.15%. As such, it is claimed unlikely that such species would be present in the conversion and granulation areas.

6.4 PARTICLE SIZE DISTRIBUTIONS

The workplace aerosols particle size characterisation was achieved using Marple cascade impactors. One of the drawbacks of the cascade impactors is that it is sometimes difficult to collect sufficient dust for the smaller particles size impactor stages. This was observed in several of the cascade impactor sets collected at both sites, with many of the impactor stages displaying masses of dust below the analytical LOD, with a similar problems also occurring for the masses of total nickel at each stage. Expert judgement was therefore used to determine whether the results from each cascade impactor could be sensibly used to determine particle size

distributions for both total dust and nickel. In terms of determining the particle size distributions, from the seven cascade impactors successfully collected at Site One, 3 dust data sets and 5 nickel data sets were assessed to be usable. From the 21 cascade impactor data sets collected at Site Two, 11 total dust and nickel data sets were determined to be usable.

Firstly focussing on total dust and nickel concentrations considering all the cascade impactor data collected, overall similar trends in exposure to that identified with the IOM sampling heads were observed. In several instances, cascade impactor and IOM samplers were either worn or used as static samplers in combination. The finding that generally higher measurements were obtained from the IOM samplers is not surprising given that the cascade impactor does not have the same capability to retain all of the sampled dust and may be expected to produce an underestimate of exposure due to internal wall losses. Irrespective of whether the sampler combinations were personal or static samples, the IOM sampling head and cascade impactor total dust data sets were considered to be comparable. For the total nickel data, whilst there was a strong correlation between the IOM sampling head and the cascade impactor, the results from measurements with the IOM sampling head were higher than the corresponding static values obtained from the cascade impactor. Different analytical techniques were used to analyse the nickel contents on the static IOM and static cascade impactor samples. For the static IOM measurements, the total nickel concentrations was determined using the speciation results obtained using the leaching and atomic absorption spectrometry method (Zatka *et al*, 1992) whereas cascade impactor substrates and personal IOM samples were determined directly using a modified digestion method and ICP/AES based on OSHA method 121 (OSHA, 1991). Some issues with Zatka method have been discussed above, although these may not affected total nickel results. Whilst the modified digestion method will undoubtedly have improved digestion of nickel oxide, we do not have any information on the recovery efficiency for nickel oxides. Without further investigation it is not possible to determine whether this or other reasons caused the discrepancy.

Although the number of 'usable' cascade impactor data sets is fewer than originally hoped, the remaining data sets are of great value. A visual inspection of the aerosol size distribution for the total nickel in the Raw materials area of Site One showed good agreement between the three usable data sets (two static and one personal) and demonstrated that the vast majority of the aerosol consisted of particles greater than a particle size of 10µm. One usable total nickel data set was plotted from Site One so it is difficult to establish whether this is a true reflection of the situation here. However the graph suggests that the aerosol in the nickel chloride area also consists predominately of particles greater than a particle size of 10µm.

For the three personal aerosol size distribution figures for total nickel collected in the raw materials area of Site two, there was generally good agreement between the particulate concentration greater than around 6 µm in size. Greater variability was observed for the smaller particles. The figures seem to suggest a possible bimodal distribution. There was little agreement between the two usable aerosol size distributions for total nickel collected in the rotary kilns area at Site Two. Whilst the static sample was placed near the mouth of the rotary kiln and suggests that the aerosol comprises mostly of particles with aerodynamic diameter of less than 10µm, the personal sample suggests predominately larger particles being present. The individual wearing the personal sample was reported to either work in the control room or move around the general work area which is likely to have resulted in a reduction in exposure to fine particulates from the kiln area. Good agreement was observed between the five aerosol size distribution figures (3 personal and 2 static) for the furnace area of Site Two and in this area there was also evidence that the majority of the aerosol consisted of particles greater than a particle size of 10µm.

The client expressed an interest in determining the proportion of aerosol which falls within the various aerosol fractions. Given the cut-offs points for the various impactor stages it is difficult to provide such information. However an approximation of particles in the respirable fraction can be provided, by looking at the percentage of the aerosol being below the aerodynamic diameter cut off point of 6μm. For Site One, between 10-26% of the mass (mean = 19%) falls within this range, with the lower respirable fraction percentage being observed in the raw materials area. At Site Two there is more variability in the respirable fraction, ranging from 12.3-63.8% with a mean value of 34% and the highest value being observed in the rotary kilns area.

6.5 APPLICATION OF METHODOLOGY TO FUTURE SAMPLING CAMPAIGNS

Upon reflection of the sampling methodology undertaken during the sampling campaigns and the results obtained various factors need to be considered and addressed when employing monitoring strategies in future campaigns. One of the major problems of using personal cascade impactors to characterise workplace aerosols is the sensitivity of the method particularly for the smaller particles size stages. This is a particular issue in premises where exposures are relatively low due to the nature of the processes or the control measures present. Consideration may need to be given to the use of other methods, for example, portable real-time monitoring equipment, to provide a more detailed evaluation of the dust fraction of the aerosol when such situations are thought to be present.

Transportation of the greased substrates used in the cascade impactor samplers posed problems due to the substrates becoming stuck to the tins. Preparation of these substrates on-site is generally not feasible given that they must be prepared, conditioned and weighed prior to use, with many industrial environments not having suitable laboratory facilities available. The use of local laboratories rather than relying on the samples to be transported by air transport may help minimise any loses.

Methodology reported by Vincent *et al* (2001) which aimed to provide direct measurements of the distributions of both particle size and relevant nickel species groups, may also be of value for future campaigns. In this work instrumentation was developed, based on a modified version of the Andersen cascade impactor, incorporating a porous foam media top stage that produced particle classification over the upper end of the inhalable range. The results of the field study provided results that could be represented succinctly in terms of the distributions of the four nickel species groups and two health-related particle-size fractions: inhalable and respirable. They showed that, for practical purposes, the distributions of the four nickel species groups were consistently uniform across the full range of particle-size distribution.

Both Sites involved in the sampling campaigns have raised concerns regarding the speciation results presented, in particular with reference to the presence of nickel species in areas where previous work by the Sites have shown them not to be present and the nature of the raw materials / products being used and/or manufactured. Several limitations of the Zatka *et al* (1992) method have been identified (ENIA, personal communication) and discussed, which may have contributed to the results obtained. It is felt that the use of the Zatka *et al* (1992) method, or any modifications / variations, for nickel speciation analyses, requires further investigation, particularly for samples collected from sites processing lateritic ores. Although XRD analysis cannot be relied upon to identify all the nickel species which may be present in a workplace environment, nor does it provide a quantitative measurement, it is useful as a preliminary qualitative assessment of the main nickel species present, which can then be used when considering further the analytical methods to be used for the quantitative assessment.

The Danish Environmental Protection Agency recently published a proposition for the Human Health Risk Reduction Strategy (RRS) for nickel and nickel compounds (Danish Environmental Protection Agency, 2006). This RRS document aims (among other scopes) to set a Community binding Occupational Exposure Limit (OEL) under the Carcinogens Directive (EC, 2004). In response to the publication of the RRS (which followed the completion of the two sampling campaigns), the findings of this research program can be used to help inform the development of a sampling methodology, based on a robust and relevant program, which will allow comparison of exposure measurements with such future measures. Careful consideration must be given to the respective advantages and limitations of the various sampling and analytical methods when developing any future sampling campaigns, with careful consideration being given to the questions to be answered and the working environment being surveyed.

7 STATEMENT OF QUALITY

IOM recognise and adopt accepted UK guidelines for good survey practice

This project was carried out under the IOM project management system, which includes preparation of a written protocol for the research and periodic auditing of the work by experienced senior scientists not actively involved in the study.

IOM has United Kingdom Accreditation Service (UKAS) accreditation for several measurement techniques. While the laboratory gravimetric analysis and total nickel analysis by Inductively Coupled Plasma/Atomic Emission Spectrometry for samples collected under this study is covered by the UKAS accreditation, the modified acid digestion method used for the total nickel analysis is out with the scope of the accreditation. Sampling and analytical quality assurance included appropriate calibration checks, replicate analyses and blank samples.

Data processing and reporting was subject to the internal data processing control procedures. Raw data is stored for five years.

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APPENDIX ONE: RESULTS OF PERSONAL AND STATIC INHALABLE DUST AND NICKEL CONCENTRATIONS (IOM SAMPLERS)

Table A1: Results of personal and static inhalable dust and nickel concentrations using IOM sampling heads)

Sample code	Job title	Time (mins)	Inhalable dust conc (mg/m3)	Total Ni conc (µg/m3)
Site One – personal samples				
QF0038	$NiCl_2$ maintenance operator	192	0.7	36.72
QF0045	Electrolysis	198	9.1	814.90
QF0046	$NiCl_2$ packing operator	195	0.8	46.67
QF0047	Nickel matte operator	185	1.5	172.97
QF0049	Electrolysis	242	0.5	6.48
QF0050	$NiCl_2$ packing operator	223	0.8	24.55
QF0053	Nickel matte operator	208	0.7	8.65
QF0057	$NiCl_2$ packing operator	220	0.5	1.82
QF0067	Electrolysis	232	0.5	2.37
Site One – static samples				
QF0036	Nickel matte store	271	5.7	2481.55
QF0042	$NiCl_2$ packing area	277	0.4	66.48
QF0043	Nickel matte caterpillar cabin	451	0.3	92.02
QF0052	Nickel matte store	482	1.1	401.82
QF0054	$NiCl_2$ packing area	519	0.2	22.45
QF0056	Electrolysis	548	0.3	19.80
QF0058	Nickel matte store	193	1.5	500.00
Site Two – personal samples				
QF0099	Raw materials operator	211	2.9	7.62
QF0101	Raw materials operator	212	2.0	0.71
QF0080	Rotary kilns operator	216	1.6	0.23
QF0103	Rotary kilns operator	221	9.3	15.16
QF0114	Rotary kilns operator	214	2.5	0.23
QF0100	Raw material operator	228	4.2	20.30
QF0115	Raw materials foreman	230	3.2	2.00
QF0062	Furnace operator	328	4.7	25.74
QF0064	Crane operator	239	3.8	16.95
QF0068	Furnace operator	319	4.0	21.91
QF0060	Furnace operator	251	4.6	31.46
QF0061	Furnace operator	240	2.2	8.74
QF0066	Furnace operator	266	25.2	170.68
QF0069	Furnace operator	299	8.6	54.35
QF0074	Crane operator	337	3.8	6.66
QF0077	Granulation operator	312	1.2	12.50
QF0079	Granulation operator	312	1.9	2.80
QF0083	Convertor operator	330	13.1	101.86
QF0089	Granulation operator	260	3.9	19.61
QF0094	Convertor operator	339	4.1	16.04
QF0108	Foreman	318	2.6	4.95

Sample code	Job title	Time (mins)	Inhalable dust conc (mg/m3)	Total Ni conc (µg/m3)
Site Two – static samples				
QF0088	Rotary kiln	301	3.0	59.00
QF0092	Raw materials	303	1.5	36.55
QF0098	Rotary kilns	298	1.8	91.28
QF0087	Metal tapping area	165	8.3	106.27
QF0090	Furnace area	283	12	127.90
QF0104	Conversion area	268	2.4	99.81
QF0086	Granulation area	280	2.9	86.09
QF0082	Conversion area	224	14.3	203.43
QF0113	Granulation area	208	2.7	72.60

Note: total nickel content for static and personal samples determined using different analytical methods.

APPENDIX TWO: RAW TOTAL DUST AND NICKEL DATA FOR CASCADE IMPACTOR ANALYSIS

SITE ONE

Cascade impactor code: CI/01/02
Type: Personal
Location: Electrolysis
Paired IOM sampler: none

Sample flow rate (l/min): 1.98
Sampling time (mins): 175
Sampling volume (m^3): 0.3465

Total Dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.75**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10} D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.025	0.0721501	1.319587	0.379383	0.190178	32.30566	9.65251	90.34749
2	14.8	0.025	0.0721501	1.171368	0.148219	0.486781	17.59859	9.65251	80.69498
3	9.8	0.025	0.0721501	0.989595	0.181773	0.396924	12.03599	9.65251	71.04247
4	6.0	0.025	0.0721501	0.78464	0.204955	0.352029	7.711128	9.65251	61.38996
5	3.5	0.025	0.0721501	0.546473	0.238167	0.302939	4.629743	9.65251	51.73745
6	1.55	0.025	0.0721501	0.166669	0.379805	0.189966	2.272851	9.65251	42.08494
7	0.93	0.059	0.1702742	-0.0439	0.210567	0.808647	1.151822	22.77992	19.30502
8	0.52	0.025	0.0721501	-0.29112	0.247217	0.291849	0.679975	9.65251	9.65251
F	0.25	0.025	0.0721501	-0.59215	0.30103	0.239677	0.361717	9.65251	0
W_{tot}		0.259	0.7474747					100	

Total Nickel **Total mass concentration C_{tot} (µg m^{-3}):** **5.48**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10} D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.5	1.4430014	1.319587	0.379383	3.80355	32.30566	26.31579	73.68421
2	14.8	0.2	0.5772006	1.171368	0.148219	3.894247	17.59859	10.52632	63.15789
3	9.8	0.2	0.5772006	0.989595	0.181773	3.17539	12.03599	10.52632	52.63158
4	6.0	0.1	0.2886003	0.78464	0.204955	1.408116	7.711128	5.263158	47.36842
5	3.5	0.3	0.8658009	0.546473	0.238167	3.635266	4.629743	15.78947	31.57895
6	1.55	0.2	0.5772006	0.166669	0.379805	1.51973	2.272851	10.52632	21.05263
7	0.93	0.2	0.5772006	-0.0439	0.210567	2.741176	1.151822	10.52632	10.52632
8	0.52	0.1	0.2886003	-0.29112	0.247217	1.167395	0.679975	5.263158	5.263158
F	0.25	0.1	0.2886003	-0.59215	0.30103	0.958709	0.361717	5.263158	0
W_{tot}		1.9	5.4834055					100	

SITE ONE

Cascade impactor code: CI/01/03

Type: Personnel

Location: Caterpillar driver

Paired IOM sampler:

Sample flow rate (l/min): 1.95

Sampling time (mins): 445

Sampling volume (m^3): 0.86775

Total Dust **Total mass concentration C_{tot} (mg m^{-3}):** **3.26**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.46	0.5301066	1.32344	0.37553	1.411621	32.44926	16.28319	83.71681
2	14.8	0.39	0.4494382	1.17499	0.14845	3.027549	17.75067	13.80531	69.9115
3	9.8	0.24	0.2765774	0.99323	0.18176	1.521664	12.13697	8.495575	61.41593
4	6.0	0.11	0.1267646	0.788259	0.204971	0.618452	7.775795	3.893805	57.52212
5	3.5	0.05	0.0576203	0.550223	0.238036	0.242065	4.669186	1.769912	55.75221
6	1.55	1.5	1.7286085	0.170084	0.380139	4.547307	2.291677	53.09735	2.654867
7	0.93	0.025	0.0288101	-0.0403	0.210384	0.13694	1.161159	0.884956	1.769912
8	0.52	0.025	0.0288101	-0.28739	0.247088	0.116599	0.685734	0.884956	0.884956
F	0.25	0.025	0.0288101	-0.58842	0.30103	0.095705	0.364835	0.884956	0
W_{tot}		2.825	3.255546					100	

Total Nickel **Total mass concentration C_{tot} (µg m^{-3}):** **275.08**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	74	85.278018	1.32344	0.37553	227.0868	32.44926	31.00126	68.99874
2	14.8	60.4	69.605301	1.17499	0.14845	468.8819	17.75067	25.30373	43.69501
3	9.8	46	53.01066	0.99323	0.18176	291.6522	12.13697	19.27105	24.42396
4	6.0	33.2	38.259867	0.788259	0.204971	186.6601	7.775795	13.90867	10.51529
5	3.5	19.9	22.932872	0.550223	0.238036	96.34184	4.669186	8.336824	2.178467
6	1.55	4.6	5.301066	0.170084	0.380139	13.94507	2.291677	1.927105	0.251362
7	0.93	0.4	0.4609623	-0.0403	0.210384	2.191047	1.161159	0.167574	0.083787
8	0.52	0.1	0.1152406	-0.28739	0.247088	0.466395	0.685734	0.041894	0.041894
F	0.25	0.1	0.1152406	-0.58842	0.30103	0.382821	0.364835	0.041894	0
W_{tot}		238.7	275.07923					100	

SITE ONE

Cascade impactor code: CI/01/04
Type: Static
Location: Nickel cutting
Paired IOM sampler: none

Sample flow rate (l/min): 1.98
Sampling time (mins): 381
Sampling volume (m^3): 0.75438

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.36**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.07	0.0927914	1.319587	0.379383	0.244585	32.30566	25.92593	74.07407
2	14.8	0.025	0.0331398	1.171368	0.148219	0.223587	17.59859	9.259259	64.81481
3	9.8	0.025	0.0331398	0.989595	0.181773	0.182314	12.03599	9.259259	55.55556
4	6.0	0.025	0.0331398	0.78464	0.204955	0.161693	7.711128	9.259259	46.2963
5	3.5	0.025	0.0331398	0.546473	0.238167	0.139145	4.629743	9.259259	37.03704
6	1.55	0.025	0.0331398	0.166669	0.379805	0.087255	2.272851	9.259259	27.77778
7	0.93	0.025	0.0331398	-0.0439	0.210567	0.157384	1.151822	9.259259	18.51852
8	0.52	0.025	0.0331398	-0.29112	0.247217	0.134051	0.679975	9.259259	9.259259
F	0.25	0.025	0.0331398	-0.59215	0.30103	0.110088	0.361717	9.259259	0
W_{tot}		0.27	0.3579098					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **7.82**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	2.1	2.7837429	1.319587	0.379383	7.337557	32.30566	35.59322	64.40678
2	14.8	1.3	1.7232694	1.171368	0.148219	11.62653	17.59859	22.0339	42.37288
3	9.8	0.4	0.5302368	0.989595	0.181773	2.917025	12.03599	6.779661	35.59322
4	6.0	0.8	1.0604735	0.78464	0.204955	5.174181	7.711128	13.55932	22.0339
5	3.5	0.6	0.7953551	0.546473	0.238167	3.339483	4.629743	10.16949	11.86441
6	1.55	0.4	0.5302368	0.166669	0.379805	1.396077	2.272851	6.779661	5.084746
7	0.93	0.1	0.1325592	-0.0439	0.210567	0.629535	1.151822	1.694915	3.389831
8	0.52	0.1	0.1325592	-0.29112	0.247217	0.536205	0.679975	1.694915	1.694915
F	0.25	0.1	0.1325592	-0.59215	0.30103	0.440352	0.361717	1.694915	0
W_{tot}		5.9	7.8209921					100	

SITE ONE

Cascade impactor code: CI/01/05
Type: Static
Location: Nickel matte store
Paired IOM sampler: QF0036

Sample flow rate (l/min): 1.95
Sampling time (mins): 271
Sampling volume (m^3): 0.52845

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **4.31**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.48	0.9083168	1.32344	0.37553	2.418757	32.44926	21.05263	78.94737
2	14.8	0.46	0.8704702	1.17499	0.14845	5.863746	17.75067	20.17544	58.77193
3	9.8	0.48	0.9083168	0.99323	0.18176	4.997345	12.13697	21.05263	37.7193
4	6.0	0.46	0.8704702	0.788259	0.204971	4.246802	7.775795	20.17544	17.54386
5	3.5	0.3	0.567698	0.550223	0.238036	2.38492	4.669186	13.15789	4.385965
6	1.55	0.025	0.0473082	0.170084	0.380139	0.12445	2.291677	1.096491	3.289474
7	0.93	0.025	0.0473082	-0.0403	0.210384	0.224865	1.161159	1.096491	2.192982
8	0.52	0.025	0.0473082	-0.28739	0.247088	0.191463	0.685734	1.096491	1.096491
F	0.25	0.025	0.0473082	-0.58842	0.30103	0.157154	0.364835	1.096491	0
W_{tot}		2.28	4.3145047					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **1259.15**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	155.4	294.06756	1.32344	0.37553	783.0725	32.44926	23.35437	76.64563
2	14.8	151.7	287.06595	1.17499	0.14845	1933.761	17.75067	22.79832	53.84731
3	9.8	155.5	294.25679	0.99323	0.18176	1618.932	12.13697	23.3694	30.47791
4	6.0	131.6	249.03018	0.788259	0.204971	1214.955	7.775795	19.77758	10.70033
5	3.5	57.7	109.18725	0.550223	0.238036	458.6996	4.669186	8.671476	2.028855
6	1.55	10.6	20.058662	0.170084	0.380139	52.76666	2.291677	1.593027	0.435828
7	0.93	2.2	4.1631186	-0.0403	0.210384	19.78815	1.161159	0.330628	0.1052
8	0.52	0.6	1.135396	-0.28739	0.247088	4.595106	0.685734	0.090171	0.015029
F	0.25	0.1	0.1892327	-0.58842	0.30103	0.628617	0.364835	0.015029	0
W_{tot}		665.4	1259.1541					100	

SITE ONE

Cascade impactor code: CI/01/07
Type: Personal
Location: NiCl2 packing operator
Paired IOM sampler: QF0046

Sample flow rate (l/min): 1.98
Sampling time (mins): 195
Sampling volume (m^3): 0.3861

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **1.24**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.025	0.0647501	1.319587	0.379383	0.170672	32.30566	5.208333	94.79167
2	14.8	0.025	0.0647501	1.171368	0.148219	0.436855	17.59859	5.208333	89.58333
3	9.8	0.025	0.0647501	0.989595	0.181773	0.356214	12.03599	5.208333	84.375
4	6.0	0.28	0.7252007	0.78464	0.204955	3.538344	7.711128	58.33333	26.04167
5	3.5	0.025	0.0647501	0.546473	0.238167	0.271868	4.629743	5.208333	20.83333
6	1.55	0.025	0.0647501	0.166669	0.379805	0.170482	2.272851	5.208333	15.625
7	0.93	0.025	0.0647501	-0.0439	0.210567	0.307504	1.151822	5.208333	10.41667
8	0.52	0.025	0.0647501	-0.29112	0.247217	0.261916	0.679975	5.208333	5.208333
F	0.25	0.025	0.0647501	-0.59215	0.30103	0.215095	0.361717	5.208333	0
W_{tot}		0.48	1.2432012					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **8.81**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	1	2.5900026	1.319587	0.379383	6.826885	32.30566	29.41176	70.58824
2	14.8	0.7	1.8130018	1.171368	0.148219	12.23193	17.59859	20.58824	50
3	9.8	0.7	1.8130018	0.989595	0.181773	9.973982	12.03599	20.58824	29.41176
4	6.0	0.1	0.2590003	0.78464	0.204955	1.263694	7.711128	2.941176	26.47059
5	3.5	0.4	1.036001	0.546473	0.238167	4.349891	4.629743	11.76471	14.70588
6	1.55	0.2	0.5180005	0.166669	0.379805	1.36386	2.272851	5.882353	8.823529
7	0.93	0.1	0.2590003	-0.0439	0.210567	1.230015	1.151822	2.941176	5.882353
8	0.52	0.1	0.2590003	-0.29112	0.247217	1.047662	0.679975	2.941176	2.941176
F	0.25	0.1	0.2590003	-0.59215	0.30103	0.86038	0.361717	2.941176	0
W_{tot}		3.4	8.8060088					100	

SITE ONE

Cascade impactor code: CI/01/09
Type: Static
Location: Electrolysis
Paired IOM sampler: QF0056

Sample flow rate (l/min): 2
Sampling time (mins): 548
Sampling volume (m^3): 1.096

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.21**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.025	0.0228102	1.317051	0.381919	0.059725	32.21148	11.11111	88.88889
2	14.8	0.025	0.0228102	1.168984	0.148067	0.154053	17.49919	11.11111	77.77778
3	9.8	0.025	0.0228102	0.987203	0.181782	0.125481	11.96998	11.11111	66.66667
4	6.0	0.025	0.0228102	0.782258	0.204944	0.1113	7.668852	11.11111	55.55556
5	3.5	0.025	0.0228102	0.544005	0.238253	0.095739	4.603961	11.11111	44.44444
6	1.55	0.025	0.0228102	0.16442	0.379585	0.060093	2.260542	11.11111	33.33333
7	0.93	0.025	0.0228102	-0.04627	0.210687	0.108266	1.145716	11.11111	22.22222
8	0.52	0.025	0.0228102	-0.29357	0.247302	0.092236	0.676211	11.11111	11.11111
F	0.25	0.025	0.0228102	-0.5946	0.30103	0.075774	0.35968	11.11111	0
W_{tot}		0.225	0.205292					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **1.09**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.1	0.0912409	1.317051	0.381919	0.238901	32.21148	8.333333	91.66667
2	14.8	0.2	0.1824818	1.168984	0.148067	1.232428	17.49919	16.66667	75
3	9.8	0.1	0.0912409	0.987203	0.181782	0.501925	11.96998	8.333333	66.66667
4	6.0	0.3	0.2737226	0.782258	0.204944	1.335595	7.668852	25	41.66667
5	3.5	0.1	0.0912409	0.544005	0.238253	0.382958	4.603961	8.333333	33.33333
6	1.55	0.1	0.0912409	0.16442	0.379585	0.24037	2.260542	8.333333	25
7	0.93	0.1	0.0912409	-0.04627	0.210687	0.433064	1.145716	8.333333	16.66667
8	0.52	0.1	0.0912409	-0.29357	0.247302	0.368944	0.676211	8.333333	8.333333
F	0.25	0.1	0.0912409	-0.5946	0.30103	0.303096	0.35968	8.333333	0
W_{tot}		1.2	1.0948905					100	

SITE ONE

Cascade impactor code: CI/01/10
Type: Static
Location: Nickel matte store
Paired IOM sampler: QF0052

Sample flow rate (l/min): 1.93
Sampling time (mins): 484
Sampling volume (m^3): 0.93412

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.62**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.07	0.0749368	1.326041	0.372929	0.200941	32.54659	12.06897	87.93103
2	14.8	0.08	0.0856421	1.177436	0.148605	0.576306	17.85411	13.7931	74.13793
3	9.8	0.12	0.1284632	0.995685	0.181751	0.706809	12.20563	20.68966	53.44828
4	6.0	0.13	0.1391684	0.790703	0.204982	0.678932	7.819769	22.41379	31.03448
5	3.5	0.08	0.0856421	0.552755	0.237948	0.359919	4.69601	13.7931	17.24138
6	1.55	0.025	0.0267632	0.17239	0.380365	0.070362	2.304478	4.310345	12.93103
7	0.93	0.025	0.0267632	-0.03787	0.210261	0.127285	1.167507	4.310345	8.62069
8	0.52	0.025	0.0267632	-0.28487	0.247001	0.108353	0.68965	4.310345	4.310345
F	0.25	0.025	0.0267632	-0.5859	0.30103	0.088905	0.366955	4.310345	0
W_{tot}		0.58	0.6209052					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **232.41**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	26.7	28.583051	1.326041	0.372929	76.64473	32.54659	12.29848	87.70152
2	14.8	26.5	28.368946	1.177436	0.148605	190.9013	17.85411	12.20636	75.49516
3	9.8	60.1	64.338629	0.995685	0.181751	353.9934	12.20563	27.6831	47.81207
4	6.0	52.8	56.523787	0.790703	0.204982	275.7507	7.819769	24.32059	23.49148
5	3.5	38	40.679998	0.552755	0.237948	170.9615	4.69601	17.50345	5.988024
6	1.55	10	10.705263	0.17239	0.380365	28.14474	2.304478	4.606172	1.381852
7	0.93	2.7	2.8904209	-0.03787	0.210261	13.7468	1.167507	1.243667	0.138185
8	0.52	0.2	0.2141053	-0.28487	0.247001	0.86682	0.68965	0.092123	0.046062
F	0.25	0.1	0.1070526	-0.5859	0.30103	0.355621	0.366955	0.046062	0
W_{tot}		217.1	232.41125					100	

SITE TWO

Cascade impactor code: CI/02/01
Type: Personal
Location: Rotary kilns - control room operator
Paired IOM sampler: QF0080

Sample flow rate (l/min): 2
Sampling time (mins): 218
Sampling volume (m^3): 0.436

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.71**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.025	0.0573394	1.317051	0.381919	0.150135	32.21148	8.064516	91.93548
2	14.8	0.025	0.0573394	1.168984	0.148067	0.387254	17.49919	8.064516	83.87097
3	9.8	0.11	0.2522936	0.987203	0.181782	1.387892	11.96998	35.48387	48.3871
4	6.0	0.025	0.0573394	0.782258	0.204944	0.279781	7.668852	8.064516	40.32258
5	3.5	0.025	0.0573394	0.544005	0.238253	0.240666	4.603961	8.064516	32.25806
6	1.55	0.025	0.0573394	0.16442	0.379585	0.151058	2.260542	8.064516	24.19355
7	0.93	0.025	0.0573394	-0.04627	0.210687	0.272155	1.145716	8.064516	16.12903
8	0.52	0.025	0.0573394	-0.29357	0.247302	0.23186	0.676211	8.064516	8.064516
F	0.25	0.025	0.0573394	-0.5946	0.30103	0.190478	0.35968	8.064516	0
W_{tot}		0.31	0.7110092					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **2.29**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.2	0.4587156	1.317051	0.381919	1.201082	32.21148	20	80
2	14.8	0.1	0.2293578	1.168984	0.148067	1.549015	17.49919	10	70
3	9.8	0.1	0.2293578	0.987203	0.181782	1.26172	11.96998	10	60
4	6.0	0.1	0.2293578	0.782258	0.204944	1.119122	7.668852	10	50
5	3.5	0.1	0.2293578	0.544005	0.238253	0.962664	4.603961	10	40
6	1.55	0.1	0.2293578	0.16442	0.379585	0.604233	2.260542	10	30
7	0.93	0.1	0.2293578	-0.04627	0.210687	1.08862	1.145716	10	20
8	0.52	0.1	0.2293578	-0.29357	0.247302	0.927438	0.676211	10	10
F	0.25	0.1	0.2293578	-0.5946	0.30103	0.76191	0.35968	10	0
W_{tot}		1	2.293578					100	

SITE TWO

Cascade impactor code: CI/02/02
Type: Personal
Location: Raw materials - control room dust collection & materials handling
Paired IOM sampler: QF0099

Sample flow rate (l/min): 2.01
Sampling time (mins): 212
Sampling volume (m^3): 0.42612

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **1.58**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.25	0.5866892	1.315793	0.383177	1.531117	32.16484	37.03704	62.96296
2	14.8	0.15	0.3520135	1.167801	0.147992	2.378606	17.45006	22.22222	40.74074
3	9.8	0.07	0.164273	0.986015	0.181786	0.90366	11.93736	10.37037	30.37037
4	6.0	0.025	0.0586689	0.781076	0.204939	0.286275	7.647958	3.703704	26.66667
5	3.5	0.025	0.0586689	0.54278	0.238296	0.246202	4.591219	3.703704	22.96296
6	1.55	0.08	0.1877405	0.163305	0.379476	0.494737	2.254459	11.85185	11.11111
7	0.93	0.025	0.0586689	-0.04744	0.210746	0.278386	1.142698	3.703704	7.407407
8	0.52	0.025	0.0586689	-0.29479	0.247345	0.237195	0.674351	3.703704	3.703704
F	0.25	0.025	0.0586689	-0.59582	0.30103	0.194894	0.358673	3.703704	0
W_{tot}		0.675	1.5840608					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **10.33**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	1.3	3.0507838	1.315793	0.383177	7.961809	32.16484	29.54545	70.45455
2	14.8	0.6	1.4080541	1.167801	0.147992	9.514425	17.45006	13.63636	56.81818
3	9.8	0.5	1.1733784	0.986015	0.181786	6.454717	11.93736	11.36364	45.45455
4	6.0	0.2	0.4693514	0.781076	0.204939	2.290198	7.647958	4.545455	40.90909
5	3.5	0.4	0.9387027	0.54278	0.238296	3.939234	4.591219	9.090909	31.81818
6	1.55	0.1	0.2346757	0.163305	0.379476	0.618421	2.254459	2.272727	29.54545
7	0.93	0.8	1.8774054	-0.04744	0.210746	8.908364	1.142698	18.18182	11.36364
8	0.52	0.1	0.2346757	-0.29479	0.247345	0.94878	0.674351	2.272727	9.090909
F	0.25	0.4	0.9387027	-0.59582	0.30103	3.118303	0.358673	9.090909	0
W_{tot}		4.4	10.32573					100	

SITE TWO

Cascade impactor code: CI/02/03
Type: Personal
Location: Rotary kilns - mostly outside control room
Paired IOM sampler: none

Sample flow rate (l/min): 2
Sampling time (mins): 232
Sampling volume (m^3): 0.464

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **3.11**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.6	1.2931034	1.317051	0.381919	3.385808	32.21148	41.52249	58.47751
2	14.8	0.19	0.4094828	1.168984	0.148067	2.765526	17.49919	13.14879	45.32872
3	9.8	0.34	0.7327586	0.987203	0.181782	4.030978	11.96998	23.52941	21.79931
4	6.0	0.025	0.0538793	0.782258	0.204944	0.262897	7.668852	1.730104	20.0692
5	3.5	0.025	0.0538793	0.544005	0.238253	0.226143	4.603961	1.730104	18.3391
6	1.55	0.025	0.0538793	0.16442	0.379585	0.141943	2.260542	1.730104	16.609
7	0.93	0.025	0.0538793	-0.04627	0.210687	0.255732	1.145716	1.730104	14.87889
8	0.52	0.025	0.0538793	-0.29357	0.247302	0.217868	0.676211	1.730104	13.14879
F	0.25	0.19	0.4094828	-0.5946	0.30103	1.360272	0.35968	13.14879	0
W_{tot}		1.445	3.1142241					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **14.66**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	3.5	7.5431034	1.317051	0.381919	19.75055	32.21148	51.47059	48.52941
2	14.8	1.4	3.0172414	1.168984	0.148067	20.37756	17.49919	20.58824	27.94118
3	9.8	0.4	0.862069	0.987203	0.181782	4.742327	11.96998	5.882353	22.05882
4	6.0	0.3	0.6465517	0.782258	0.204944	3.154767	7.668852	4.411765	17.64706
5	3.5	0.1	0.2155172	0.544005	0.238253	0.904573	4.603961	1.470588	16.17647
6	1.55	0.1	0.2155172	0.16442	0.379585	0.567771	2.260542	1.470588	14.70588
7	0.93	0.6	1.2931034	-0.04627	0.210687	6.137562	1.145716	8.823529	5.882353
8	0.52	0.1	0.2155172	-0.29357	0.247302	0.871472	0.676211	1.470588	4.411765
F	0.25	0.3	0.6465517	-0.5946	0.30103	2.147798	0.35968	4.411765	0
W_{tot}		6.8	14.655172					100	

Cascade impactor code: CI/02/04

Type: Personal

Location: Raw materials - control room operator

Paired IOM sampler: QF0100

Sample flow rate (l/min): 2

Sampling time (mins): 228

Sampling volume (m^3): 0.456

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **4.18**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.98	2.1491228	1.317051	0.381919	5.627173	32.21148	51.44357	48.55643
2	14.8	0.35	0.7675439	1.168984	0.148067	5.183765	17.49919	18.3727	30.18373
3	9.8	0.07	0.1535088	0.987203	0.181782	0.844467	11.96998	3.674541	26.50919
4	6.0	0.025	0.0548246	0.782258	0.204944	0.267509	7.668852	1.312336	25.19685
5	3.5	0.025	0.0548246	0.544005	0.238253	0.230111	4.603961	1.312336	23.88451
6	1.55	0.025	0.0548246	0.16442	0.379585	0.144433	2.260542	1.312336	22.57218
7	0.93	0.025	0.0548246	-0.04627	0.210687	0.260218	1.145716	1.312336	21.25984
8	0.52	0.025	0.0548246	-0.29357	0.247302	0.22169	0.676211	1.312336	19.94751
F	0.25	0.38	0.8333333	-0.5946	0.30103	2.768273	0.35968	19.94751	0
W_{tot}		1.905	4.1776316					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **49.78**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	8.8	19.298246	1.317051	0.381919	50.52972	32.21148	38.76652	61.23348
2	14.8	3.5	7.6754386	1.168984	0.148067	51.83765	17.49919	15.4185	45.81498
3	9.8	0.5	1.0964912	0.987203	0.181782	6.031907	11.96998	2.202643	43.61233
4	6.0	0.3	0.6578947	0.782258	0.204944	3.210114	7.668852	1.321586	42.29075
5	3.5	0.2	0.4385965	0.544005	0.238253	1.840885	4.603961	0.881057	41.40969
6	1.55	0.1	0.2192982	0.16442	0.379585	0.577732	2.260542	0.440529	40.96916
7	0.93	0.2	0.4385965	-0.04627	0.210687	2.081746	1.145716	0.881057	40.08811
8	0.52	0.9	1.9736842	-0.29357	0.247302	7.980851	0.676211	3.964758	36.12335
F	0.25	8.2	17.982456	-0.5946	0.30103	59.73643	0.35968	36.12335	0
W_{tot}		22.7	49.780702					100	

SITE TWO

Cascade impactor code: CI/02/05
Type: Personal
Location: Raw materials - foreman
Paired IOM sampler: QF0115

Sample flow rate (l/min): 2
Sampling time (mins): 230
Sampling volume (m^3): 0.46

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **2.01**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.48	1.0434783	1.317051	0.381919	2.7322	32.21148	51.89189	48.10811
2	14.8	0.08	0.173913	1.168984	0.148067	1.174557	17.49919	8.648649	39.45946
3	9.8	0.1	0.2173913	0.987203	0.181782	1.195891	11.96998	10.81081	28.64865
4	6.0	0.14	0.3043478	0.782258	0.204944	1.485027	7.668852	15.13514	13.51351
5	3.5	0.025	0.0543478	0.544005	0.238253	0.22811	4.603961	2.702703	10.81081
6	1.55	0.025	0.0543478	0.16442	0.379585	0.143177	2.260542	2.702703	8.108108
7	0.93	0.025	0.0543478	-0.04627	0.210687	0.257956	1.145716	2.702703	5.405405
8	0.52	0.025	0.0543478	-0.29357	0.247302	0.219763	0.676211	2.702703	2.702703
F	0.25	0.025	0.0543478	-0.5946	0.30103	0.18054	0.35968	2.702703	0
W_{tot}		0.925	2.0108696					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **7.17**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.9	1.9565217	1.317051	0.381919	5.122874	32.21148	27.27273	72.72727
2	14.8	0.6	1.3043478	1.168984	0.148067	8.80918	17.49919	18.18182	54.54545
3	9.8	0.3	0.6521739	0.987203	0.181782	3.587673	11.96998	9.090909	45.45455
4	6.0	0.2	0.4347826	0.782258	0.204944	2.121467	7.668852	6.060606	39.39394
5	3.5	0.7	1.5217391	0.544005	0.238253	6.38707	4.603961	21.21212	18.18182
6	1.55	0.3	0.6521739	0.16442	0.379585	1.718124	2.260542	9.090909	9.090909
7	0.93	0.1	0.2173913	-0.04627	0.210687	1.031822	1.145716	3.030303	6.060606
8	0.52	0.1	0.2173913	-0.29357	0.247302	0.87905	0.676211	3.030303	3.030303
F	0.25	0.1	0.2173913	-0.5946	0.30103	0.722158	0.35968	3.030303	0
W_{tot}		3.3	7.173913					100	

SITE TWO

Cascade impactor code: CI/02/06
Type: Personal
Location: Raw materials - control room silos
Paired IOM sampler: QF0101

Sample flow rate (l/min): 2.05
Sampling time (mins): 211
Sampling volume (m^3): 0.43255

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.52**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.025	0.0577968	1.310821	0.388149	0.148903	31.98124	11.11111	88.88889
2	14.8	0.025	0.0577968	1.163127	0.147694	0.391329	17.25734	11.11111	77.77778
3	9.8	0.025	0.0577968	0.981324	0.181803	0.317908	11.80933	11.11111	66.66667
4	6.0	0.025	0.0577968	0.776405	0.204919	0.282047	7.565966	11.11111	55.55556
5	3.5	0.025	0.0577968	0.537941	0.238464	0.242371	4.541224	11.11111	44.44444
6	1.55	0.025	0.0577968	0.158896	0.379044	0.15248	2.230584	11.11111	33.33333
7	0.93	0.025	0.0577968	-0.05209	0.210982	0.273942	1.130851	11.11111	22.22222
8	0.52	0.025	0.0577968	-0.2996	0.247512	0.233511	0.667051	11.11111	11.11111
F	0.25	0.025	0.0577968	-0.60063	0.30103	0.191997	0.354722	11.11111	0
W_{tot}		0.225	0.5201711					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **6.01**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	1.6	3.6989943	1.310821	0.388149	9.529823	31.98124	61.53846	38.46154
2	14.8	0.1	0.2311871	1.163127	0.147694	1.565315	17.25734	3.846154	34.61538
3	9.8	0.1	0.2311871	0.981324	0.181803	1.271633	11.80933	3.846154	30.76923
4	6.0	0.1	0.2311871	0.776405	0.204919	1.12819	7.565966	3.846154	26.92308
5	3.5	0.3	0.6935614	0.537941	0.238464	2.908449	4.541224	11.53846	15.38462
6	1.55	0.1	0.2311871	0.158896	0.379044	0.609921	2.230584	3.846154	11.53846
7	0.93	0.1	0.2311871	-0.05209	0.210982	1.095769	1.130851	3.846154	7.692308
8	0.52	0.1	0.2311871	-0.2996	0.247512	0.934046	0.667051	3.846154	3.846154
F	0.25	0.1	0.2311871	-0.60063	0.30103	0.767987	0.354722	3.846154	0
W_{tot}		2.6	6.0108658					100	

SITE TWO

Cascade impactor code: CI/02/07
Type: Static
Location: Static - top end rotary kilns
Paired IOM sampler: QF0088

Sample flow rate (l/min): 2
Sampling time (mins): 301
Sampling volume (m^3): 0.602

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **1.54**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.32	0.5315615	1.317051	0.381919	1.391818	32.21148	34.59459	65.40541
2	14.8	0.11	0.1827243	1.168984	0.148067	1.234066	17.49919	11.89189	53.51351
3	9.8	0.11	0.1827243	0.987203	0.181782	1.005184	11.96998	11.89189	41.62162
4	6.0	0.025	0.0415282	0.782258	0.204944	0.202632	7.668852	2.702703	38.91892
5	3.5	0.025	0.0415282	0.544005	0.238253	0.174303	4.603961	2.702703	36.21622
6	1.55	0.025	0.0415282	0.16442	0.379585	0.109404	2.260542	2.702703	33.51351
7	0.93	0.025	0.0415282	-0.04627	0.210687	0.197109	1.145716	2.702703	30.81081
8	0.52	0.025	0.0415282	-0.29357	0.247302	0.167925	0.676211	2.702703	28.10811
F	0.25	0.26	0.4318937	-0.5946	0.30103	1.43472	0.35968	28.10811	0
W_{tot}		0.925	1.5365449					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **20.1**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	2.8	4.6511628	1.317051	0.381919	12.17841	32.21148	23.1405	76.8595
2	14.8	0.1	0.166113	1.168984	0.148067	1.121878	17.49919	0.826446	76.03306
3	9.8	1.3	2.1594684	0.987203	0.181782	11.87945	11.96998	10.7438	65.28926
4	6.0	1	1.6611296	0.782258	0.204944	8.105271	7.668852	8.264463	57.02479
5	3.5	1.5	2.4916944	0.544005	0.238253	10.45818	4.603961	12.39669	44.6281
6	1.55	2.7	4.4850498	0.16442	0.379585	11.81567	2.260542	22.31405	22.31405
7	0.93	0.7	1.1627907	-0.04627	0.210687	5.519048	1.145716	5.785124	16.52893
8	0.52	0.8	1.3289037	-0.29357	0.247302	5.373596	0.676211	6.61157	9.917355
F	0.25	1.2	1.9933555	-0.5946	0.30103	6.621784	0.35968	9.917355	0
W_{tot}		12.1	20.099668					100	

SITE TWO

Cascade impactor code: CI/02/08
Type: Static
Location: Static - mixed raw materials conveyor
Paired IOM sampler: QF0092

Sample flow rate (l/min): 2.03
Sampling time (mins): 303
Sampling volume (m^3): 0.61509

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.46**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.08	0.1300623	1.313294	0.385676	0.337232	32.07246	28.57143	71.42857
2	14.8	0.025	0.0406445	1.165453	0.147842	0.274918	17.35296	8.928571	62.5
3	9.8	0.025	0.0406445	0.983658	0.181795	0.223573	11.87286	8.928571	53.57143
4	6.0	0.025	0.0406445	0.778729	0.204929	0.198334	7.60665	8.928571	44.64286
5	3.5	0.025	0.0406445	0.540349	0.23838	0.170502	4.56603	8.928571	35.71429
6	1.55	0.025	0.0406445	0.16109	0.379259	0.107168	2.242431	8.928571	26.78571
7	0.93	0.025	0.0406445	-0.04978	0.210865	0.192751	1.13673	8.928571	17.85714
8	0.52	0.025	0.0406445	-0.2972	0.247429	0.164267	0.670673	8.928571	8.928571
F	0.25	0.025	0.0406445	-0.59823	0.30103	0.135018	0.356682	8.928571	0
W_{tot}		0.28	0.4552179					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **2.93**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.5	0.8128892	1.313294	0.385676	2.107702	32.07246	27.77778	72.22222
2	14.8	0.4	0.6503113	1.165453	0.147842	4.398695	17.35296	22.22222	50
3	9.8	0.1	0.1625778	0.983658	0.181795	0.894293	11.87286	5.555556	44.44444
4	6.0	0.1	0.1625778	0.778729	0.204929	0.793338	7.60665	5.555556	38.88889
5	3.5	0.3	0.4877335	0.540349	0.23838	2.04603	4.56603	16.66667	22.22222
6	1.55	0.1	0.1625778	0.16109	0.379259	0.428672	2.242431	5.555556	16.66667
7	0.93	0.1	0.1625778	-0.04978	0.210865	0.771006	1.13673	5.555556	11.11111
8	0.52	0.1	0.1625778	-0.2972	0.247429	0.65707	0.670673	5.555556	5.555556
F	0.25	0.1	0.1625778	-0.59823	0.30103	0.540072	0.356682	5.555556	0
W_{tot} (7)		1.8	2.926401					100	

SITE TWO

Cascade impactor code: CI/02/09
Type: Static
Location: Static - end of rotary kiln area before transfer to furnace
Paired IOM sampler: QF0098

Sample flow rate (l/min): 1.99
Sampling time (mins): 301
Sampling volume (m^3): 0.59899

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.92**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.19	0.3172006	1.318316	0.380654	0.833304	32.25842	34.54545	65.45455
2	14.8	0.025	0.0417369	1.170173	0.148143	0.281735	17.54869	4.545455	60.90909
3	9.8	0.06	0.1001686	0.988396	0.181778	0.551051	12.00286	10.90909	50
4	6.0	0.09	0.1502529	0.783446	0.20495	0.733121	7.689908	16.36364	33.63636
5	3.5	0.05	0.0834738	0.545236	0.23821	0.350421	4.616802	9.090909	24.54545
6	1.55	0.025	0.0417369	0.165542	0.379695	0.109922	2.266673	4.545455	20
7	0.93	0.025	0.0417369	-0.04509	0.210627	0.198156	1.148757	4.545455	15.45455
8	0.52	0.025	0.0417369	-0.29235	0.24726	0.168798	0.678086	4.545455	10.90909
F	0.25	0.06	0.1001686	-0.59338	0.30103	0.332753	0.360695	10.90909	0
W_{tot}		0.55	0.9182123					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **9.68**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.5	0.8347385	1.318316	0.380654	2.192906	32.25842	8.62069	91.37931
2	14.8	0.3	0.5008431	1.170173	0.148143	3.380817	17.54869	5.172414	86.2069
3	9.8	0.6	1.0016862	0.988396	0.181778	5.510507	12.00286	10.34483	75.86207
4	6.0	0.7	1.1686339	0.783446	0.20495	5.702055	7.689908	12.06897	63.7931
5	3.5	0.5	0.8347385	0.545236	0.23821	3.504209	4.616802	8.62069	55.17241
6	1.55	0.9	1.5025293	0.165542	0.379695	3.957206	2.266673	15.51724	39.65517
7	0.93	0.7	1.1686339	-0.04509	0.210627	5.548359	1.148757	12.06897	27.58621
8	0.52	0.5	0.8347385	-0.29235	0.24726	3.375954	0.678086	8.62069	18.96552
F	0.25	1.1	1.8364246	-0.59338	0.30103	6.100471	0.360695	18.96552	0
W_{tot}		5.8	9.6829663					100	

SITE TWO

Cascade impactor code: CI/02/12
Type: Personal
Location: Feeds furnace 1&2
Paired IOM sampler: QF0060

Sample flow rate (l/min): 2.05
Sampling time (mins): 252
Sampling volume (m^3): 0.5166

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **2.5**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.64	1.2388695	1.310821	0.388149	3.191735	31.98124	49.6124	50.3876
2	14.8	0.16	0.3097174	1.163127	0.147694	2.097025	17.25734	12.4031	37.9845
3	9.8	0.16	0.3097174	0.981324	0.181803	1.703585	11.80933	12.4031	25.5814
4	6.0	0.025	0.0483933	0.776405	0.204919	0.236159	7.565966	1.937984	23.64341
5	3.5	0.025	0.0483933	0.537941	0.238464	0.202937	4.541224	1.937984	21.70543
6	1.55	0.025	0.0483933	0.158896	0.379044	0.127672	2.230584	1.937984	19.76744
7	0.93	0.07	0.1355014	-0.05209	0.210982	0.642242	1.130851	5.426357	14.34109
8	0.52	0.025	0.0483933	-0.2996	0.247512	0.195519	0.667051	1.937984	12.4031
F	0.25	0.16	0.3097174	-0.60063	0.30103	1.028859	0.354722	12.4031	0
W_{tot}		1.29	2.4970964					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **17.23**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	2.6	5.0329075	1.310821	0.388149	12.96642	31.98124	29.21348	70.78652
2	14.8	1.2	2.3228804	1.163127	0.147694	15.72769	17.25734	13.48315	57.30337
3	9.8	1.2	2.3228804	0.981324	0.181803	12.77689	11.80933	13.48315	43.82022
4	6.0	0.8	1.5485869	0.776405	0.204919	7.557082	7.565966	8.988764	34.83146
5	3.5	0.3	0.5807201	0.537941	0.238464	2.435249	4.541224	3.370787	31.46067
6	1.55	0.5	0.9678668	0.158896	0.379044	2.55344	2.230584	5.617978	25.8427
7	0.93	1.1	2.129307	-0.05209	0.210982	10.09238	1.130851	12.35955	13.48315
8	0.52	0.2	0.3871467	-0.2996	0.247512	1.564156	0.667051	2.247191	11.23596
F	0.25	1	1.9357336	-0.60063	0.30103	6.430368	0.354722	11.23596	0
W_{tot}		8.9	17.228029					100	

SITE TWO

Cascade impactor code: CI/02/13
Type: Personal
Location: Furnace area crane operator
Paired IOM sampler: QF0064

Sample flow rate (l/min): 1.95
Sampling time (mins): 237
Sampling volume (m^3): 0.46215

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **1.17**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.15	0.3245699	1.32344	0.37553	0.864297	32.44926	27.77778	72.22222
2	14.8	0.18	0.3894839	1.17499	0.14845	2.623679	17.75067	33.33333	38.88889
3	9.8	0.025	0.054095	0.99323	0.18176	0.297618	12.13697	4.62963	34.25926
4	6.0	0.025	0.054095	0.788259	0.204971	0.263916	7.775795	4.62963	29.62963
5	3.5	0.025	0.054095	0.550223	0.238036	0.227255	4.669186	4.62963	25
6	1.55	0.025	0.054095	0.170084	0.380139	0.142303	2.291677	4.62963	20.37037
7	0.93	0.025	0.054095	-0.0403	0.210384	0.257124	1.161159	4.62963	15.74074
8	0.52	0.025	0.054095	-0.28739	0.247088	0.21893	0.685734	4.62963	11.11111
F	0.25	0.06	0.129828	-0.58842	0.30103	0.431279	0.364835	11.11111	0
W_{tot}		0.54	1.1684518					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **6.28**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.9	1.9474197	1.32344	0.37553	5.185784	32.44926	31.03448	68.96552
2	14.8	0.3	0.6491399	1.17499	0.14845	4.372799	17.75067	10.34483	58.62069
3	9.8	0.3	0.6491399	0.99323	0.18176	3.571415	12.13697	10.34483	48.27586
4	6.0	0.2	0.4327599	0.788259	0.204971	2.111325	7.775795	6.896552	41.37931
5	3.5	0.4	0.8655199	0.550223	0.238036	3.636081	4.669186	13.7931	27.58621
6	1.55	0.3	0.6491399	0.170084	0.380139	1.707638	2.291677	10.34483	17.24138
7	0.93	0.1	0.21638	-0.0403	0.210384	1.028498	1.161159	3.448276	13.7931
8	0.52	0.1	0.21638	-0.28739	0.247088	0.87572	0.685734	3.448276	10.34483
F	0.25	0.3	0.6491399	-0.58842	0.30103	2.156396	0.364835	10.34483	0
$W_{tot\ (7)}$		2.9	6.2750189					100	

SITE TWO

Cascade impactor code: CI/02/14
Type: Personal
Location: Feeds furnace four
Paired IOM sampler: none

Sample flow rate (l/min): 2
Sampling time (mins): 234
Sampling volume (m^3): 0.468

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **1.19**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.33	0.7051282	1.317051	0.381919	1.846278	32.21148	59.45946	40.54054
2	14.8	0.025	0.0534188	1.168984	0.148067	0.360775	17.49919	4.504505	36.03604
3	9.8	0.05	0.1068376	0.987203	0.181782	0.587724	11.96998	9.009009	27.02703
4	6.0	0.025	0.0534188	0.782258	0.204944	0.26065	7.668852	4.504505	22.52252
5	3.5	0.025	0.0534188	0.544005	0.238253	0.22421	4.603961	4.504505	18.01802
6	1.55	0.025	0.0534188	0.16442	0.379585	0.14073	2.260542	4.504505	13.51351
7	0.93	0.025	0.0534188	-0.04627	0.210687	0.253546	1.145716	4.504505	9.009009
8	0.52	0.025	0.0534188	-0.29357	0.247302	0.216006	0.676211	4.504505	4.504505
F	0.25	0.025	0.0534188	-0.5946	0.30103	0.177453	0.35968	4.504505	0
W_{tot}		0.555	1.1858974					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **9.62**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	1.2	2.5641026	1.317051	0.381919	6.713739	32.21148	26.66667	73.33333
2	14.8	0.5	1.0683761	1.168984	0.148067	7.215496	17.49919	11.11111	62.22222
3	9.8	0.3	0.6410256	0.987203	0.181782	3.526346	11.96998	6.666667	55.55556
4	6.0	0.3	0.6410256	0.782258	0.204944	3.127803	7.668852	6.666667	48.88889
5	3.5	1.8	3.8461538	0.544005	0.238253	16.14314	4.603961	40	8.888889
6	1.55	0.1	0.2136752	0.16442	0.379585	0.562918	2.260542	2.222222	6.666667
7	0.93	0.1	0.2136752	-0.04627	0.210687	1.014184	1.145716	2.222222	4.444444
8	0.52	0.1	0.2136752	-0.29357	0.247302	0.864024	0.676211	2.222222	2.222222
F	0.25	0.1	0.2136752	-0.5946	0.30103	0.709814	0.35968	2.222222	0
W_{tot}		4.5	9.6153846					100	

SITE TWO

Cascade impactor code: CI/02/15
Type: Personal
Location: Feeds furnace 3
Paired IOM sampler: QF0062

Sample flow rate (l/min): 1.98
Sampling time (mins): 328
Sampling volume (m^3): 0.64944

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **7.05**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	2.52	3.8802661	1.319587	0.379383	10.22784	32.30566	55.02183	44.97817
2	14.8	1.15	1.7707563	1.171368	0.148219	11.94691	17.59859	25.10917	19.869
3	9.8	0.61	0.9392708	0.989595	0.181773	5.16727	12.03599	13.31878	6.550218
4	6.0	0.12	0.1847746	0.78464	0.204955	0.901538	7.711128	2.620087	3.930131
5	3.5	0.025	0.0384947	0.546473	0.238167	0.161629	4.629743	0.545852	3.384279
6	1.55	0.025	0.0384947	0.166669	0.379805	0.101354	2.272851	0.545852	2.838428
7	0.93	0.025	0.0384947	-0.0439	0.210567	0.182815	1.151822	0.545852	2.292576
8	0.52	0.025	0.0384947	-0.29112	0.247217	0.155712	0.679975	0.545852	1.746725
F	0.25	0.08	0.1231831	-0.59215	0.30103	0.409205	0.361717	1.746725	0
W_{tot}		4.58	7.0522296					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **38.34**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	10.7	16.475733	1.319587	0.379383	43.42773	32.30566	42.97189	57.02811
2	14.8	7	10.778517	1.171368	0.148219	72.72032	17.59859	28.11245	28.91566
3	9.8	2.6	4.0034491	0.989595	0.181773	22.02443	12.03599	10.44177	18.4739
4	6.0	0.7	1.0778517	0.78464	0.204955	5.258972	7.711128	2.811245	15.66265
5	3.5	0.5	0.7698941	0.546473	0.238167	3.232579	4.629743	2.008032	13.65462
6	1.55	0.2	0.3079576	0.166669	0.379805	0.810831	2.272851	0.803213	12.85141
7	0.93	0.1	0.1539788	-0.0439	0.210567	0.731259	1.151822	0.401606	12.4498
8	0.52	0.3	0.4619364	-0.29112	0.247217	1.868544	0.679975	1.204819	11.24498
F	0.25	2.8	4.3114068	-0.59215	0.30103	14.32218	0.361717	11.24498	0
W_{tot}		24.9	38.340724					100	

SITE TWO

Cascade impactor code: CI/02/16
Type: Personal
Feeds
Location: furnace 2
Paired IOM sampler: QF0068

Sample flow rate (l/min): 1.98
Sampling time (mins): 318
Sampling volume (m^3): 0.62964

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **2.18**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.69	1.0958643	1.319587	0.379383	2.888545	32.30566	50.36496	49.63504
2	14.8	0.23	0.3652881	1.171368	0.148219	2.46452	17.59859	16.78832	32.84672
3	9.8	0.14	0.2223493	0.989595	0.181773	1.223224	12.03599	10.21898	22.62774
4	6.0	0.11	0.174703	0.78464	0.204955	0.852398	7.711128	8.029197	14.59854
5	3.5	0.025	0.0397052	0.546473	0.238167	0.166712	4.629743	1.824818	12.77372
6	1.55	0.025	0.0397052	0.166669	0.379805	0.104541	2.272851	1.824818	10.94891
7	0.93	0.025	0.0397052	-0.0439	0.210567	0.188564	1.151822	1.824818	9.124088
8	0.52	0.025	0.0397052	-0.29112	0.247217	0.160609	0.679975	1.824818	7.29927
F	0.25	0.1	0.1588209	-0.59215	0.30103	0.527592	0.361717	7.29927	0
W_{tot}		1.37	2.1758465					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **16.36**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	2.9	4.6058065	1.319587	0.379383	12.14026	32.30566	28.15534	71.84466
2	14.8	1.4	2.2234928	1.171368	0.148219	15.00142	17.59859	13.59223	58.25243
3	9.8	1.6	2.5411346	0.989595	0.181773	13.9797	12.03599	15.53398	42.71845
4	6.0	0.8	1.2705673	0.78464	0.204955	6.199255	7.711128	7.76699	34.95146
5	3.5	1.3	2.0646719	0.546473	0.238167	8.669005	4.629743	12.62136	22.3301
6	1.55	1.2	1.905851	0.166669	0.379805	5.017975	2.272851	11.65049	10.67961
7	0.93	0.5	0.7941046	-0.0439	0.210567	3.771272	1.151822	4.854369	5.825243
8	0.52	0.2	0.3176418	-0.29112	0.247217	1.284869	0.679975	1.941748	3.883495
F	0.25	0.4	0.6352837	-0.59215	0.30103	2.110367	0.361717	3.883495	0
W_{tot}		10.3	16.358554					100	

SITE TWO

Cascade impactor code: CI/02/17

Type: Personal

Location : Feeds furnace 4

Paired IOM sampler: QF0066

Sample flow rate (l/min): 2.05

Sampling time (mins): 266

Sampling volume (m^3): 0.5453

Total dust **Total mass concentration C_{tot} (mg m^{-3}): 31.63**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	7.89	14.4691	1.310821	0.388149	37.27715	31.98124	45.73913	54.26087
2	14.8	1.66	3.0441959	1.163127	0.147694	20.61155	17.25734	9.623188	44.63768
3	9.8	4.37	8.0139373	0.981324	0.181803	44.08026	11.80933	25.33333	19.30435
4	6.0	2.4	4.401247	0.776405	0.204919	21.47802	7.565966	13.91304	5.391304
5	3.5	0.66	1.2103429	0.537941	0.238464	5.075572	4.541224	3.826087	1.565217
6	1.55	0.025	0.0458463	0.158896	0.379044	0.120952	2.230584	0.144928	1.42029
7	0.93	0.07	0.1283697	-0.05209	0.210982	0.60844	1.130851	0.405797	1.014493
8	0.52	0.025	0.0458463	-0.2996	0.247512	0.185229	0.667051	0.144928	0.869565
F	0.25	0.15	0.2750779	-0.60063	0.30103	0.913789	0.354722	0.869565	0
W_{tot}		17.25	31.633963					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}): 184.85**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	25.1	46.029708	1.310821	0.388149	118.5876	31.98124	24.90079	75.09921
2	14.8	29.4	53.915276	1.163127	0.147694	365.0479	17.25734	29.16667	45.93254
3	9.8	21.2	38.877682	0.981324	0.181803	213.8448	11.80933	21.03175	24.90079
4	6.0	12.7	23.289932	0.776405	0.204919	113.6545	7.565966	12.59921	12.30159
5	3.5	4.4	8.0689529	0.537941	0.238464	33.83714	4.541224	4.365079	7.936508
6	1.55	1.5	2.7507794	0.158896	0.379044	7.257145	2.230584	1.488095	6.448413
7	0.93	0.8	1.4670823	-0.05209	0.210982	6.953599	1.130851	0.793651	5.654762
8	0.52	0.8	1.4670823	-0.2996	0.247512	5.927328	0.667051	0.793651	4.861111
F	0.25	4.9	8.9858793	-0.60063	0.30103	29.85045	0.354722	4.861111	0
W_{tot}		100.8	184.85237					100	

SITE TWO

Cascade impactor code: CI/02/18
Type: Static
Location: Static - loading of furnaces
Paired IOM sampler: QF0090

Sample flow rate (l/min): 1.98
Sampling time (mins): 282
Sampling volume (m^3): 0.55836

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **16.93**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	5.96	10.674117	1.319587	0.379383	28.13548	32.30566	63.03543	36.96457
2	14.8	2.14	3.8326528	1.171368	0.148219	25.85808	17.59859	22.63353	14.33104
3	9.8	0.9	1.6118633	0.989595	0.181773	8.867446	12.03599	9.518773	4.812269
4	6.0	0.19	0.3402823	0.78464	0.204955	1.660279	7.711128	2.009519	2.80275
5	3.5	0.11	0.1970055	0.546473	0.238167	0.827173	4.629743	1.163406	1.639344
6	1.55	0.025	0.044774	0.166669	0.379805	0.117887	2.272851	0.26441	1.374934
7	0.93	0.025	0.044774	-0.0439	0.210567	0.212636	1.151822	0.26441	1.110524
8	0.52	0.025	0.044774	-0.29112	0.247217	0.181112	0.679975	0.26441	0.846113
F	0.25	0.08	0.1432767	-0.59215	0.30103	0.475955	0.361717	0.846113	0
W_{tot}		9.455	16.93352					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **108.17**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	21.9	39.222007	1.319587	0.379383	103.3837	32.30566	36.25828	63.74172
2	14.8	16.9	30.267211	1.171368	0.148219	204.2063	17.59859	27.98013	35.76159
3	9.8	4.7	8.4175084	0.989595	0.181773	46.30777	12.03599	7.781457	27.98013
4	6.0	1.7	3.0446307	0.78464	0.204955	14.85513	7.711128	2.81457	25.16556
5	3.5	2.3	4.1192062	0.546473	0.238167	17.29545	4.629743	3.807947	21.35762
6	1.55	10.5	18.805072	0.166669	0.379805	49.51247	2.272851	17.38411	3.97351
7	0.93	0.7	1.2536715	-0.0439	0.210567	5.953795	1.151822	1.15894	2.81457
8	0.52	0.9	1.6118633	-0.29112	0.247217	6.520024	0.679975	1.490066	1.324503
F	0.25	0.8	1.4327674	-0.59215	0.30103	4.75955	0.361717	1.324503	0
W_{tot}		60.4	108.17394					100	

SITE TWO

Cascade impactor code: CI/02/20
Type: Static
Location: Static - metal tapping
Paired IOM sampler: QF0087

Sample flow rate (l/min): 1.98
Sampling time (mins): 285
Sampling volume (m^3): 0.5643

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **6.95**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	2.02	3.5796562	1.319587	0.379383	9.435473	32.30566	51.53061	48.46939
2	14.8	1.19	2.1088074	1.171368	0.148219	14.22767	17.59859	30.35714	18.11224
3	9.8	0.28	0.49619	0.989595	0.181773	2.729721	12.03599	7.142857	10.96939
4	6.0	0.24	0.4253057	0.78464	0.204955	2.075119	7.711128	6.122449	4.846939
5	3.5	0.025	0.0443027	0.546473	0.238167	0.186015	4.629743	0.637755	4.209184
6	1.55	0.025	0.0443027	0.166669	0.379805	0.116646	2.272851	0.637755	3.571429
7	0.93	0.025	0.0443027	-0.0439	0.210567	0.210397	1.151822	0.637755	2.933673
8	0.52	0.025	0.0443027	-0.29112	0.247217	0.179205	0.679975	0.637755	2.295918
F	0.25	0.09	0.1594896	-0.59215	0.30103	0.529813	0.361717	2.295918	0
W_{tot}		3.92	6.9466596					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **34.56**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	11	19.493177	1.319587	0.379383	51.38129	32.30566	56.41026	43.58974
2	14.8	0.3	0.5316321	1.171368	0.148219	3.586807	17.59859	1.538462	42.05128
3	9.8	2.7	4.784689	0.989595	0.181773	26.32231	12.03599	13.84615	28.20513
4	6.0	1.6	2.8353713	0.78464	0.204955	13.83413	7.711128	8.205128	20
5	3.5	0.7	1.2404749	0.546473	0.238167	5.208422	4.629743	3.589744	16.41026
6	1.55	0.2	0.3544214	0.166669	0.379805	0.933167	2.272851	1.025641	15.38462
7	0.93	0.2	0.3544214	-0.0439	0.210567	1.683178	1.151822	1.025641	14.35897
8	0.52	1.4	2.4809498	-0.29112	0.247217	10.0355	0.679975	7.179487	7.179487
F	0.25	1.4	2.4809498	-0.59215	0.30103	8.241537	0.361717	7.179487	0
W_{tot}		19.5	34.556087					100	

SITE TWO

Cascade impactor code: CI/02/22
Type: Personal
Location: Granulation
Paired IOM sampler: QF0079

Sample flow rate (l/min): 2
Sampling time (mins): 311
Sampling volume (m^3): 0.622

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.74**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.16	0.2572347	1.317051	0.381919	0.673533	32.21148	34.78261	65.21739
2	14.8	0.025	0.0401929	1.168984	0.148067	0.271451	17.49919	5.434783	59.78261
3	9.8	0.025	0.0401929	0.987203	0.181782	0.221105	11.96998	5.434783	54.34783
4	6.0	0.06	0.096463	0.782258	0.204944	0.470679	7.668852	13.04348	41.30435
5	3.5	0.025	0.0401929	0.544005	0.238253	0.168698	4.603961	5.434783	35.86957
6	1.55	0.025	0.0401929	0.16442	0.379585	0.105887	2.260542	5.434783	30.43478
7	0.93	0.025	0.0401929	-0.04627	0.210687	0.190771	1.145716	5.434783	25
8	0.52	0.025	0.0401929	-0.29357	0.247302	0.162525	0.676211	5.434783	19.56522
F	0.25	0.09	0.1446945	-0.5946	0.30103	0.480665	0.35968	19.56522	0
W_{tot}		0.46	0.7395498					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **3.22**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.1	0.1607717	1.317051	0.381919	0.420958	32.21148	5	95
2	14.8	0.2	0.3215434	1.168984	0.148067	2.171609	17.49919	10	85
3	9.8	0.4	0.6430868	0.987203	0.181782	3.537684	11.96998	20	65
4	6.0	0.4	0.6430868	0.782258	0.204944	3.13786	7.668852	20	45
5	3.5	0.2	0.3215434	0.544005	0.238253	1.349588	4.603961	10	35
6	1.55	0.1	0.1607717	0.16442	0.379585	0.423546	2.260542	5	30
7	0.93	0.1	0.1607717	-0.04627	0.210687	0.763084	1.145716	5	25
8	0.52	0.1	0.1607717	-0.29357	0.247302	0.650101	0.676211	5	20
F	0.25	0.4	0.6430868	-0.5946	0.30103	2.136288	0.35968	20	0
W_{tot}		2	3.2154341					100	

SITE TWO

Cascade impactor code: CI/02/23
Type: Personal
Location: Conversion/Granulation crane operator
Paired IOM sampler: QF0074

Sample flow rate (l/min): 2
Sampling time (mins): 335
Sampling volume (m^3): 0.67

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.49**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.025	0.0373134	1.317051	0.381919	0.0977	32.21148	7.575758	92.42424
2	14.8	0.07	0.1044776	1.168984	0.148067	0.705611	17.49919	21.21212	71.21212
3	9.8	0.05	0.0746269	0.987203	0.181782	0.41053	11.96998	15.15152	56.06061
4	6.0	0.025	0.0373134	0.782258	0.204944	0.182066	7.668852	7.575758	48.48485
5	3.5	0.025	0.0373134	0.544005	0.238253	0.156613	4.603961	7.575758	40.90909
6	1.55	0.025	0.0373134	0.16442	0.379585	0.098301	2.260542	7.575758	33.33333
7	0.93	0.025	0.0373134	-0.04627	0.210687	0.177104	1.145716	7.575758	25.75758
8	0.52	0.025	0.0373134	-0.29357	0.247302	0.150882	0.676211	7.575758	18.18182
F	0.25	0.06	0.0895522	-0.5946	0.30103	0.297486	0.35968	18.18182	0
W_{tot}		0.33	0.4925373					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **3.88**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.1	0.1492537	1.317051	0.381919	0.3908	32.21148	3.846154	96.15385
2	14.8	1.1	1.641791	1.168984	0.148067	11.08817	17.49919	42.30769	53.84615
3	9.8	0.3	0.4477612	0.987203	0.181782	2.463179	11.96998	11.53846	42.30769
4	6.0	0.1	0.1492537	0.782258	0.204944	0.728265	7.668852	3.846154	38.46154
5	3.5	0.1	0.1492537	0.544005	0.238253	0.62645	4.603961	3.846154	34.61538
6	1.55	0.1	0.1492537	0.16442	0.379585	0.393203	2.260542	3.846154	30.76923
7	0.93	0.1	0.1492537	-0.04627	0.210687	0.708415	1.145716	3.846154	26.92308
8	0.52	0.2	0.2985075	-0.29357	0.247302	1.207054	0.676211	7.692308	19.23077
F	0.25	0.5	0.7462687	-0.5946	0.30103	2.479051	0.35968	19.23077	0
W_{tot}		2.6	3.880597					100	

SITE TWO

Cascade impactor code: CI/02/27
Type: Personal
Location: Granulation operator
Paired IOM sampler: QF0077

Sample flow rate (l/min): 1.98
Sampling time (mins): 313
Sampling volume (m^3): 0.61974

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.4**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.025	0.0403395	1.319587	0.379383	0.106329	32.30566	10	90
2	14.8	0.025	0.0403395	1.171368	0.148219	0.272162	17.59859	10	80
3	9.8	0.025	0.0403395	0.989595	0.181773	0.221922	12.03599	10	70
4	6.0	0.025	0.0403395	0.78464	0.204955	0.196821	7.711128	10	60
5	3.5	0.025	0.0403395	0.546473	0.238167	0.169375	4.629743	10	50
6	1.55	0.025	0.0403395	0.166669	0.379805	0.106211	2.272851	10	40
7	0.93	0.025	0.0403395	-0.0439	0.210567	0.191576	1.151822	10	30
8	0.52	0.025	0.0403395	-0.29112	0.247217	0.163174	0.679975	10	20
F	0.25	0.05	0.080679	-0.59215	0.30103	0.26801	0.361717	20	0
W_{tot}		0.25	0.403395					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **1.61**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.2	0.322716	1.319587	0.379383	0.850634	32.30566	20	80
2	14.8	0.1	0.161358	1.171368	0.148219	1.088647	17.59859	10	70
3	9.8	0.1	0.161358	0.989595	0.181773	0.887689	12.03599	10	60
4	6.0	0.1	0.161358	0.78464	0.204955	0.787286	7.711128	10	50
5	3.5	0.1	0.161358	0.546473	0.238167	0.677499	4.629743	10	40
6	1.55	0.1	0.161358	0.166669	0.379805	0.424845	2.272851	10	30
7	0.93	0.1	0.161358	-0.0439	0.210567	0.766303	1.151822	10	20
8	0.52	0.1	0.161358	-0.29112	0.247217	0.652697	0.679975	10	10
F	0.25	0.1	0.161358	-0.59215	0.30103	0.53602	0.361717	10	0
W_{tot}		1	1.6135799					100	

SITE TWO

Cascade impactor code: CI/02/19
Type: Static
Location: Static - conversion area
Paired IOM sampler: QF0104

Sample flow rate (l/min): 1.925
Sampling time (mins): 268
Sampling volume (m^3): 0.5159

Total dust **Total mass concentration C_{tot} (mg m^{-3}):** **0.76**

Stage number	Cut-Point Dp (µm)	Weight Gain W (mg)	Conc ΔC (mg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (mg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.19	0.3682884	1.326695	0.372275	0.989292	32.57112	48.71795	51.28205
2	14.8	0.025	0.048459	1.178051	0.148645	0.326006	17.88023	6.410256	44.87179
3	9.8	0.025	0.048459	0.996302	0.181749	0.266626	12.22297	6.410256	38.46154
4	6.0	0.025	0.048459	0.791318	0.204984	0.236404	7.830872	6.410256	32.05128
5	3.5	0.025	0.048459	0.553392	0.237926	0.203673	4.702784	6.410256	25.64103
6	1.55	0.025	0.048459	0.172971	0.380421	0.127382	2.30771	6.410256	19.23077
7	0.93	0.025	0.048459	-0.03726	0.21023	0.230504	1.16911	6.410256	12.82051
8	0.52	0.025	0.048459	-0.28424	0.246979	0.196207	0.690639	6.410256	6.410256
F	0.25	0.025	0.048459	-0.58527	0.30103	0.160977	0.367491	6.410256	0
W_{tot}		0.39	0.7559605					100	

Total nickel **Total mass concentration C_{tot} (µg m^{-3}):** **5.43**

Stage number	Cut-Point Dp (µm)	Mass Ni W (µg)	Total nickel conc ΔC (µg m^{-3})	$\log_{10}D_p$	$\Delta\log_{10}D_p$	$\Delta C/\Delta\log_{10}D_p$ (µg m^{-3} $\log_{10}$µm)	GMD (µm)	W/W_{tot} (%)	% < D_p
1	21.3	0.8	1.5506881	1.326695	0.372275	4.165442	32.57112	28.57143	71.42857
2	14.8	0.1	0.193836	1.178051	0.148645	1.304024	17.88023	3.571429	67.85714
3	9.8	0.4	0.7753441	0.996302	0.181749	4.266024	12.22297	14.28571	53.57143
4	6.0	0.1	0.193836	0.791318	0.204984	0.945614	7.830872	3.571429	50
5	3.5	0.1	0.193836	0.553392	0.237926	0.81469	4.702784	3.571429	46.42857
6	1.55	0.4	0.7753441	0.172971	0.380421	2.038119	2.30771	14.28571	32.14286
7	0.93	0.1	0.193836	-0.03726	0.21023	0.922017	1.16911	3.571429	28.57143
8	0.52	0.4	0.7753441	-0.28424	0.246979	3.139314	0.690639	14.28571	14.28571
F	0.25	0.4	0.7753441	-0.58527	0.30103	2.575637	0.367491	14.28571	0
W_{tot}		2.8	5.4274084					100	

APPENDIX THREE: RESULTS OF CASCADE IMPACTOR DUST AND NICKEL CONCENTRATIONS

Table A3: Results of cascade impactor dust and nickel concentrations

Sample code	Description	Time (mins)	Dust conc (mg/m^3)	Ni conc ($\mu g/m^3$)
Site One				
CI/01/02	Personal - Electrolysis	175	0.75	5.48
CI/01/03	Personal - Caterpillar driver	445	3.26	275.08
CI/01/04	Static -Nickel cutting	381	0.36	7.82
CI/01/05	Static -Nickel matte store	271	4.31	1259.15
CI/01/07	Personal -Nickel chloride packing operator	195	1.24	8.81
CI/01/09	Static - Electrolysis	548	0.21	1.09
CI/01/10	Static -Nickel matte store	484	0.62	232.41
Site Two				
CI/02/01	Personal -Rotary kilns	218	0.71	2.29
CI/02/02	Personal - Raw materials	212	1.58	10.33
CI/02/03	Personal -Rotary kilns	232	3.11	14.66
CI/02/04	Personal - Raw materials	228	4.18	49.78
CI/02/05	Personal - Raw materials	230	2.01	7.17
CI/02/06	Personal - Raw materials	211	0.52	6.01
CI/02/07	Static - Rotary kilns	301	1.54	20.10
CI/02/08	Static - Raw materials	303	0.46	2.93
CI/02/09	Static - Rotary kilns	301	0.92	9.68
CI/02/12	Personal - Furnaces	252	2.50	17.23
CI/02/13	Personal - Furnace crane operator	237	1.17	6.28
CI/02/14	Personal -Furnaces	234	1.19	9.62
CI/02/15	Personal - Furnaces	328	7.05	38.34
CI/02/16	Personal - Furnaces	318	2.18	16.36
CI/02/17	Personal -Furnaces	266	31.63	184.85
CI/02/18	Static - Loading furnaces	282	16.93	108.17
CI/02/19	Static - Conversion	268	0.76	5.43
CI/02/20	Static - Metal tapping	285	6.95	34.56
CI/02/22	Personal - Granulation	311	0.74	3.22
CI/02/23	Personal - Conversion / granulation	335	0.49	3.88
CI/02/27	Personal - Granulation	313	0.40	1.61

APPENDIX FOUR: TOTAL DUST AEROSOL SIZE DISTRIBUTIONS ASSESSED BY CASCADE IMPACTORS

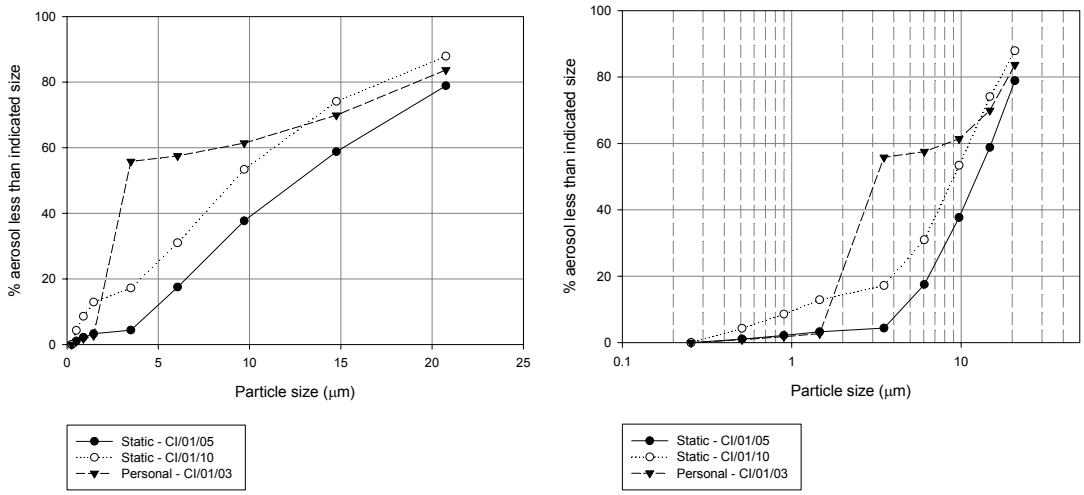

Figure A4.1 Nickel matte raw materials (Site One) Aerosol size distributions (total dust) assessed by cascade impactors (linear scale left and log scale right)

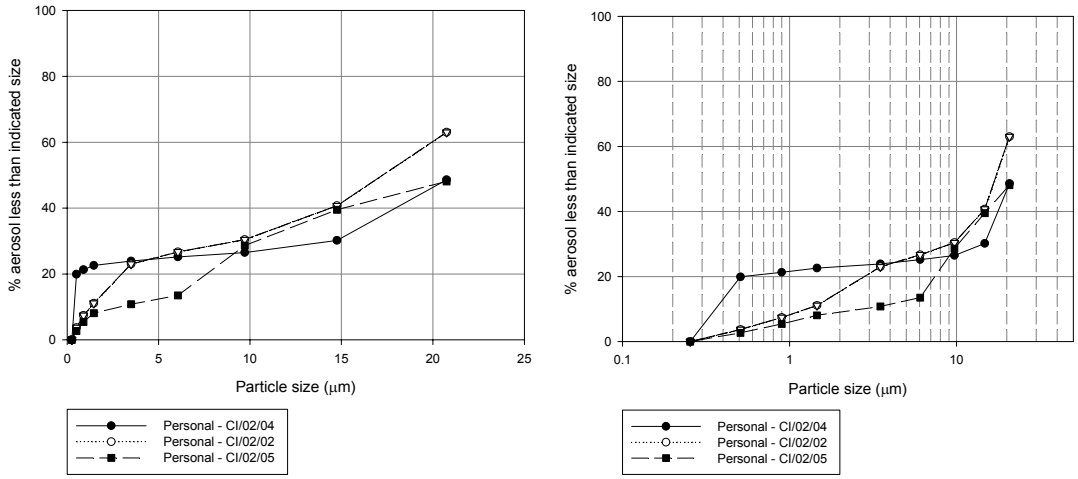

Figure A4.2 Raw materials (Site Two) Aerosol size distributions (total dust) assessed by cascade impactors (linear scale left and log scale right)

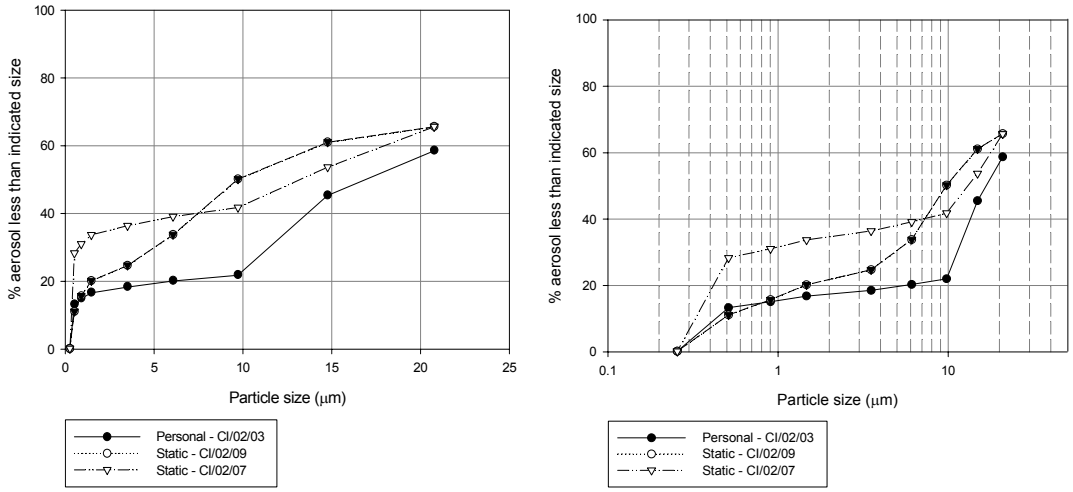

Figure A4.3 Rotary kilns (Site Two) Aerosol size distributions (total dust) assessed by cascade impactors (linear scale left and log scale right)

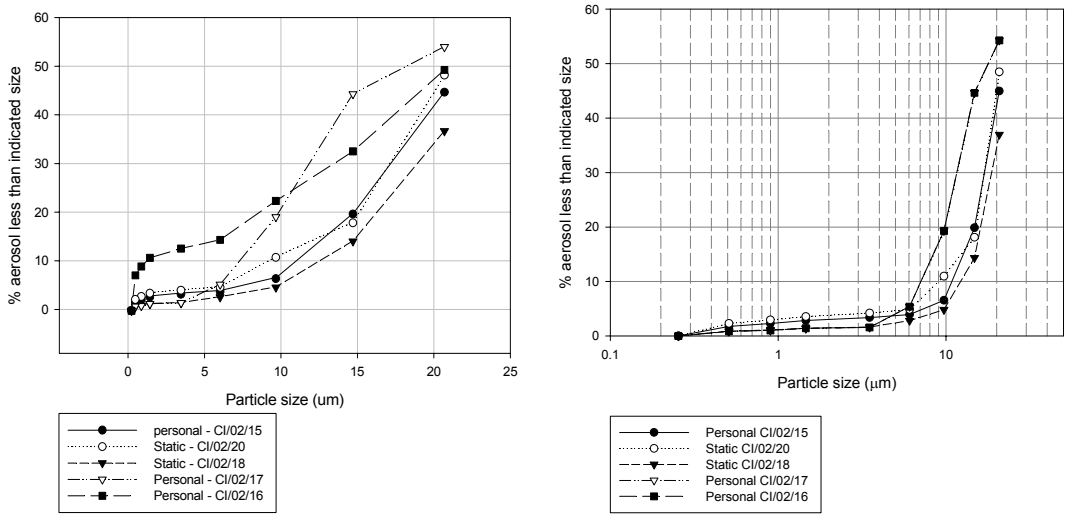

Figure A4.4 Furnace (Site Two) Aerosol size distributions (total dust) assessed by personal cascade impactors (linear scale left and log scale right)

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