Measuring Occupational Dust Exposure with a Passive Sampler

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For my mother, Elaheh. Thank you for always supporting me. And for feeding me constantly during this process.

For my sister, Mona. Thank you, my person, for always being there for me. And for your endless teasing.

I only succeed a little bit, because I fail a lot.
— Jared Leto

I did then what I knew how to do. Now that I know better, I do better.
— Maya Angelou
Abstract

Objectives: In a working environment it is important to measure dust exposure to evaluate possible health issues. Passive sampling could be an alternative to active sampling with pumps when measuring occupational dust exposure. One passive sampler is the University of North Carolina passive aerosol sampler (UNC sampler). Promising results for the applicability of this type of passive sampler have been shown for particles above 2.5 µm, but indicate large underestimations for PM$_{2.5}$. The overall purpose was to develop more knowledge about the UNC sampler and the possibility of using it for personal sampling of occupational dust exposure. Specific aims were to: evaluate and possibly improve the UNC sampler for stationary sampling in a working environment and compare the UNC sampler with commonly used aerosol sampling methods; characterise the impairment in performance of the UNC sampler concentrations when decreasing the number of images in order to achieve lowered costs and decreased analysis time, and; establish if the UNC sampler could be used for personal sampling in the working environment.

Methods: All sample collection in this thesis was performed in an open pit mine. For stationary sampling UNC samplers, impactors (PM$_{10}$ and PM$_{2.5}$), respirable cyclones, and an aerodynamic particle sizer were used. For personal sampling UNC samplers and respirable cyclones were used. The analysis of the UNC sampler consisted of two parts, the microscopic imaging of the deposited particles and the analysis model for calculations of mass concentration.

Results: In the first pilot study the UNC sampler with its original analysis model was used. Compared to PM$_{10}$ impactor concentrations the UNC sampler showed 58% of the impactor results and 35% of PM$_{2.5}$ impactor results. The second study showed that a new analysis model and use of higher microscopy resolution led to no underestimation compared to PM$_{2.5}$ impactors, while PM$_{10}$ improved but not to the same extent. A higher precision was also achieved compared to the respirable cyclone (intraclass correlation: 0.51 versus 0.24). When UNC sampler particle
size distributions were compared to aerodynamic particle sizer data, they showed similar distributions for the new analysis model, but deviating distributions for the original analysis model. In the third study the number of images needed from the microscopic imaging process was reduced. Reducing the number of images analysed from 60 to 10 increased the coefficient of variation from 36% to 37% for respirable fraction. Finally, the UNC sampler was used for personal sampling in a working environment for the first time. Again, the particle size distribution of the new UNC sampler analysis model was reasonable, while the distribution of the original model was not. There were almost exclusively particles of mineral origin on the UNC sampler, but compared to the respirable cyclone, the UNC sampler overestimated the particle concentrations approximately 30 times.

**Conclusions:** The new analysis model for the UNC sampler enables stationary passive sampling of dust exposure of mineral character. Quicker microscopic image analysis, by reducing the number of images for mass concentration calculations to ten, results in a negligible loss in precision. Personal sampling with the UNC sampler showed deposited particles of reasonable size distribution and obviously originating from the working environment, but with severe overestimation of the mass concentration. Thus, the UNC sampler with the new analysis model can be used for stationary sampling in a mine, but is not yet ready for personal sampling.

**Keywords:** dust particles; mineral; PM$_{10}$; PM$_{2.5}$; respirable fraction; UNC passive aerosol sampler; working environment
Sammanfattning


Arbetsmiljön som valdes för att undersöka den passiva provtagaren i var en gruva (dagbrott). Då provtagaren aldrig används i gruvan tidigare togs även impaktorer, cykloner och andra typer av provtagare med som det redan finns kunskap om och som redan blivit testade. Mätningarna utfördes på två olika vis, både på olika platser i gruvan och även på olika personer. För att utvärdera resultatet av den passiva provtagaren tas bilder på dammet med ett avancerat mikroskop. Informationen från bilderna görs sedan om till koncentrationen av dammet för att kunna jämföra detta med de andra provtagarna.

Efter de första mätningarna visade den passiva provtagaren lägre koncentrationer jämfört med impaktorerna. Då tidigare studier visat att den passiva provtagaren stämde bra överens för större partiklar gjordes fler mätningar. Från den andra vändan av mätningar upptäcktes återigen samma fenomen. Det som inte hade tagits

Om hänsyn tas till att modellen måste ändras då det är vindstilla kan den passiva provtagaren användas för platsmätningar i gruvmiljön. För personburen provtagning mätte den passiva provtagaren dammet från arbetsmiljön och inte till exempel hud eller textilier. Den visade dock mycket högre koncentrationer av damm än jämförelseprovtagaren. Således kan den passiva provtagaren användas för platsmätningar i gruvmiljön, men den är ännu inte redo för personburen provtagning.
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>APS</td>
<td>Aerodynamic Particle Sizer</td>
</tr>
<tr>
<td>CT</td>
<td>Carbon Tab</td>
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<tr>
<td>CV</td>
<td>Coefficient of Variation</td>
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<tr>
<td>CV&lt;sub&gt;ws&lt;/sub&gt;</td>
<td>Within-Sampler Coefficient of Variation</td>
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<tr>
<td>DALY</td>
<td>Disability-Adjusted Life Year</td>
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<td>EDS</td>
<td>Energy Dispersive X-ray Spectroscopy</td>
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<td>FRM</td>
<td>Federal Reference Method</td>
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<tr>
<td>ICC</td>
<td>Intraclass Correlation</td>
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<tr>
<td>IOM</td>
<td>Institute of Occupational Medicine</td>
</tr>
<tr>
<td>OEL</td>
<td>Occupational Exposure Limit</td>
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<tr>
<td>PAH</td>
<td>Polycyclic Aromatic Hydrocarbon</td>
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<tr>
<td>PC</td>
<td>Polycarbonate</td>
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<tr>
<td>PM</td>
<td>Particulate Matter</td>
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<tr>
<td>PM&lt;sub&gt;10&lt;/sub&gt;</td>
<td>PM passing through an inlet with 50% cut-off at 10 µm</td>
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<tr>
<td>PM&lt;sub&gt;2.5&lt;/sub&gt;</td>
<td>PM passing through an inlet with 50% cut-off at 2.5 µm</td>
</tr>
<tr>
<td>PM&lt;sub&gt;10−2.5&lt;/sub&gt;</td>
<td>PM&lt;sub&gt;10&lt;/sub&gt;−PM&lt;sub&gt;2.5&lt;/sub&gt;</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope/Microscopy</td>
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<tr>
<td>UNC sampler</td>
<td>University of North Carolina passive aerosol sampler</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>---------</td>
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<tr>
<td>WHO</td>
<td>World Health Organization</td>
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<tr>
<td>XRD</td>
<td>X-ray Diffraction</td>
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Nomenclature

\( \gamma_{\text{mesh}} \)  
Empirical modifier to account for the mesh cap

\( \eta \)  
Dynamic viscosity [kg m\(^{-1}\)s\(^{-1}\)]

\( \rho_0 \)  
Unit particle density, 1 000 kg m\(^{-3}\) [kg m\(^{-3}\)]

\( \rho_{\text{air}} \)  
Density of air [kg m\(^{-3}\)]

\( \rho_p \)  
Particle density [kg m\(^{-3}\)]

\( A \)  
Area [m\(^2\)]

\( A_T \)  
Total area [m\(^2\)]

\( C \)  
Mass concentration [kg m\(^{-3}\)]

\( C_c \)  
Cunningham slip correction factor

\( C_{c,da} \)  
Cunningham correction factor for a particle with diameter \( d_a \)

\( C_{c,dev} \)  
Cunningham correction factor for a particle with diameter \( d_{ev} \)

\( D \)  
Hole size [m]

\( d_a \)  
Aerodynamic diameter [m]

\( d_{ev} \)  
Equivalent volume diameter [m]

\( d_p \)  
Particle diameter [m]

\( d_{pa} \)  
Projected area diameter [m]

\( F_B \)  
Buoyancy force [N]
\( F_D \) Drag force [N]
\( F_{mg} \) Gravitational force [N]
\( g \) Gravitational acceleration [m s\(^{-2}\)]
\( j_m \) Mass flux [kg m\(^{-2}\)s\(^{-1}\)]
\( m \) Mass [kg]
\( P \) Pitch [m]
\( S_d \) Dynamic shape factor
\( S_v \) Volume shape factor
\( t \) Time [s]
\( V_{sphere} \) Volume of sphere [m\(^3\)]
\( v \) Velocity [m s\(^{-1}\)]
\( v_{dep} \) Deposition velocity [m s\(^{-1}\)]
\( v_{ts} \) Terminal settling velocity [m s\(^{-1}\)]
List of Papers

This thesis is based on the following papers:


III Shirdel M, Sommar JN, Andersson BM, Bergdahl IA, Wingfors H, Liljelind IE. Choosing the Number of Images and Image Position When Analysing the UNC Passive Aerosol Sampler for Occupational Exposure Assessment. (Manuscript).


The papers will be referred to by their Roman numerals I-IV.
Preface

In this thesis I invite you to explore the world of passive particle sampling of occupational exposure. As air pollution is becoming an ever increasing problem, it is not only important to combat air pollution, but to offer cheap and simple instruments to monitor people’s exposure. As I sit here writing this, there are people in some places in the People’s Republic of China that are told to stay indoors because of the air pollution levels. Focusing on particles, we are not only bombarded with them outdoors, we are also exposed to them indoors and at work.

In general, a person in Sweden spends about eight hours, five days a week, at work, for about 45 weeks each year. Let us say that the starting age is 24 years old as a worker, after both some travelling, studying and perhaps military service. In Sweden the lowest retirement age is 61 years. Thus, a person works a minimum of 37 years, five days a week, for eight hours. A regular person is then not only exposed to indoor and outdoor particles, but to particles at work for about 66 600 hours. That is a whole lot of time to be exposed to particles, especially at jobs with particle exposures that can affect health. Not only is it important to know what and how much particles a person is exposed to, it is also important to know where they go in the body and how they react when they deposit.

In a world where words such as ‘evidence-based’ and ‘science-based’ are on the verge of being censored in the United States of America, a country that withdrew from the Paris agreement in 2017, it is more important than ever to protect the planet and the people living on it. Every single person deserves the chance to live a life without impaired health and living conditions because of the consequences of being subjected to air pollution.

Mariam Shirdel,
Umeå, Sweden,
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Chapter 1

Introduction

In occupational hygiene, development of personal sampling instruments have been made because of the need to make health risk assessments of personal exposure (Walton and Vincent, 1998). For health risk assessments, not only particle mass concentrations, but also e.g. surface area, number of particles, particle size distribution, chemical composition and morphology are important to know. This need arises from not having enough information when making assessments knowing only concentration (Walton and Vincent, 1998; Brown et al., 2001; Stoeger et al., 2006; Ghio et al., 2012). To be able to make all of these assessments, using only one instrument encompassing all of the aforementioned properties would be beneficial. Passive samplers, by using analysis methods resulting in the aforementioned properties, could be one such type of instrument for measuring occupational particle exposure.

1.1 Aerosols

To be able to understand how measurement instruments operate in order to use them for exposure assessment we need to know a bit about aerosols. In the field of aerosols (airborne particles), as described in Hinds (1999), the diameter of an irregular particle, \( d_p \), is usually described in terms of the aerodynamic diameter, \( d_a \). The aerodynamic diameter is the diameter of a sphere with a unit density, \( \rho_0 = 1\ 000\ kg\ m^{-3} \), with the same terminal settling velocity, \( v_{ts} \), as the irregular particle. The terminal settling velocity is the velocity the particle reaches when all forces acting on it are in equilibrium. To be able to investigate how a particle moves, we need to know the forces acting on it. The forces acting on a settling particle are the
gravitational force, $F_{mg}$, the drag force, $F_D$, and the buoyancy force, $F_B$, as seen in Fig. 1.1.

![Diagram of forces acting on a particle falling through air: Drag force, Buoyancy force, Gravitational force](image)

**Figure 1.1: The forces acting on a particle falling through air.**

When terminal settling velocity is reached all forces are in balance

$$F_{mg} = F_D + F_B.$$  \hfill (1.1)

In the case of small particle size and low velocity we can assume the drag force to be described by Stoke’s drag force law. We know that

$$F_{mg} = \rho_0 \frac{V_{sphere}}{g},$$ \hfill (1.2)

$$F_D = 3\pi \eta d_a v,$$ \hfill (1.3)

$$F_B = \rho_{air} g \frac{V_{sphere}}{g},$$ \hfill (1.4)

where $V_{sphere}$ is the volume of the aerodynamic equivalent sphere; $g$ is the gravitational acceleration; $\eta$ is the dynamic viscosity of the air; $\rho_{air}$ is the density of air; and the velocity $v = v_{air} - v_p$, where the air is assumed to be motionless ($v_{air} = 0$). When the forces are in equilibrium the velocity is equal to the terminal settling velocity, and inserting Eqns. (1.2)-(1.4) in Eqn. (1.1) we get

$$v_{ts} = \frac{\rho_0 d_a^2 g}{18 \eta},$$ \hfill (1.5)
1.2. PARTICLE SIZE FRACTIONS RELATED TO HEALTH

with the assumption that $\rho_0 \gg \rho_{\text{air}}$.

For particles smaller than 1 $\mu$m Stoke’s law has to be adjusted to take the slip effect into account. Slip is when the particles are so small that the surrounding gas (air in our case) is no longer a continuous medium and the particle senses all the molecules. The terminal settling velocity expression is amended by introducing the Cunningham slip correction factor, $C_c$, such that

$$v_{ts} = \frac{\rho_0 d_a^2 g C_{c,da}}{18 \eta}, \quad (1.6)$$

where $C_{c,da}$ is the Cunningham slip correction factor for a particle with diameter $d_a$.

1.2 Particle size fractions related to health

Particles deposited in the respiratory system are hazardous to different extent depending on the composition and where in the system they deposit (Hinds, 1999). The respiratory system is divided into three regions: head airways, lung airways (tracheobronchial), and pulmonary (alveolar). The head airways region consists of the nose, mouth, pharynx and larynx (Fig. 1.2). The lung airways region consists of the trachea, bronchi, and terminal bronchioles (right before the alveoli). The alveolar region consists of the alveoli and is where gas exchange takes place.
Deposition of particles in the respiratory system is mainly due to impaction, settling, and diffusion. There is no exact size limit that defines which particles deposit where in the respiratory system. Generally, particles larger than 10 µm do not reach the alveolar region, and particles between 2–10 µm are diminished in that region.

The different particle sizes are divided into particle size fractions used for health related sampling for workplace atmospheres, and are defined as inhalable fraction, extrathoracic fraction, thoracic fraction, tracheobronchial and respirable fraction (EN 481:1993; ISO 7708:1995). Although ISO 7708:1995 does state that the standard is for airborne particles in the workplace and ambient environment.
1.3. OCCUPATIONAL RISKS DUE TO AIRBORNE PARTICULATES

The criteria for the different particle size fractions defined by EN 481:1993 and ISO 7708:1995 are:

- **Inhalable fraction** – the mass fraction of total airborne particles which is inhaled through the nose and mouth.

- **Extrathoracic fraction** – the mass fraction of inhaled particles failing to penetrate beyond the larynx.

- **Thoracic fraction** – the mass fraction of inhaled particles penetrating beyond the larynx.

- **Tracheobronchial fraction** – the mass fraction of inhaled particles penetrating beyond the larynx, but failing to penetrate to the unciliated airways.

- **Respirable fraction** – the mass fraction of inhaled particles penetrating to the unciliated airways.

These criteria are based on particles penetrating to a region, and not if the particles are deposited there. The inhalable fraction consists of particles that are 100 µm or smaller. The thoracic and respirable fractions have median diameters of 11.64 µm and 4.25 µm respectively.

The particle size fractions used for health related sampling in ambient environments for atmospheric aerosol particles (particulate matter, PM) are: ultrafine PM (principally less than 0.1 µm); PM$_{2.5}$ (PM passing through an inlet with 50% cut-off at 2.5 µm); PM$_{10}$ (PM passing through an inlet with 50% cut-off at 10 µm); and PM$_{10-2.5}$ (PM$_{10}$—PM$_{2.5}$). There are no standards or regulations for PM$_{10-2.5}$ and ultrafine PM. The standards for PM$_{2.5}$ and PM$_{10}$ are defined as fraction of suspended particulate matter which passes through a size-selective inlet with a 50% cut-off efficiency at 2.5 µm and 10 µm aerodynamic diameter, respectively (EN 12341:2014). The definitions for PM$_{2.5}$ and PM$_{10}$ in the Swedish air quality regulations are also consistent with EN 12341:2014 (SFS 2010:477).

1.3 Occupational risks due to airborne particulates

One of the occupational risks as stated by the World Health Organization (WHO) is airborne particulates. The estimated deaths by WHO, attributable to occupational airborne particulate exposure, were 457 000 in 2004, which is 0.8% of total deaths for all causes, with 46 000 estimated deaths in Europe and 19 000 estimated deaths in high income countries in Europe (i.e. Sweden). Estimated disability-adjusted life years (DALYs) attributable to airborne particulates were 6 751 000, 0.4% of
total DALYs due to all causes, with 676 000 DALYs in Europe and 284 000 in high income countries in Europe (i.e. Sweden). In Sweden, of the approved work-related diseases for 2013 and 2014, 5% were prescribed to respiratory disease (AFA Försäkring). Thus, airborne particulates due to occupational exposure is a risk, affecting people all over the world.

1.4 Health effects due to occupational dust exposure

Walton and Vincent (1998) state that “The health and well-being of the individual worker should not be impaired during his or her livelihood.”, which is why it is of utmost importance to study the health effects due to occupational dust exposure to be able to take preventive measures.

Bergdahl et al. (2004) and Torén and Järvelöm (2014) found that there was an increased mortality due to chronic obstructive pulmonary disease among construction workers exposed to inorganic dust. Meo et al. (2013) discovered that cement mill workers exposed to cement dust had impaired lung function, and Torén et al. (2011) found that exposure to inorganic dust increases mortality from infectious pneumonia for construction workers. Sjödahl et al. (2007) learned that there was an increased risk of gastric cancer for male Swedish construction workers exposed to quartz dust and cement dust, and in the meta analysis written by Lee et al. (2016) it was concluded that there was a higher risk of gastric cancer for workers exposed to crystalline silica. Another meta-analysis study found that occupational exposure to silica dust increases the risk of lung cancer and that workers in the mining industry had the highest risk (Poinen-Rughooputh et al., 2016). Occupational exposure to particles have been associated with an increased risk for coronary heart disease (Torén et al., 2007; Ohlson et al., 2010; Wiebert et al., 2012).

1.5 Sampling of particles

There are different types of instruments to sample particles for exposure assessments. Active sampling of particles entails sampling with the help of a power supply to run the instrument. For ambient air stationary (area) sampling of airborne PM, instruments like impactors and cyclones are usually used to meet the criteria and legislations for PM$_{2.5}$ and PM$_{10}$ (Heal et al., 2012). Impactors have an inlet which draws in particles by using a pump. The impactor operates in a way that the particles that are bigger than a specific size impact on a plate. The particles below that size go around the plate following the air stream onto a filter to be collected. The cyclone is similar to an impactor such that a pump is used to draw
1.5. SAMPLING OF PARTICLES

in the air containing particles. The air is circulated at high speed in the cyclone, which separates the smaller particles from the larger ones. The larger ones fall to the bottom while the smaller ones are collected on a filter. To measure inhalable and respirable fractions in the working environment, the IOM (Institute of Occupational Medicine) sampler and respirable cyclones are used, respectively (Kenny, 1996; Koehler and Peters, 2015).

In recent years cheaper and lighter alternatives for stationary and personal sampling have been developed to enable more and easier sampling. For ambient air PM exposure Han et al. (2017) tried a low-cost, portable, direct reading instrument. Lee et al. (2006) developed a personal respirable particulate sampler for ambient air measurements, covering a range of PM and gaseous pollutants. Volckens et al. (2017) developed an ultrasonic personal aerosol sampler run with a piezoelectric pump for PM$_2.5$ personal exposure assessments for both outdoor, indoor, and occupational use. Stewart et al. (2017) developed a disposable aerosol sampler for easier exposure assessments of inhalable particulates in working environments.

1.5.1 Respirable cyclone for exposure assessment

To assess the occupational exposure of the respirable fraction for an individual, personal sampling is employed with a respirable cyclone (Walton and Vincent, 1998; Koehler and Peters, 2015). The respirable cyclone was developed by miniaturising previous cyclones used in the 1970s, as a result of wanting a personal sampler small enough for the worker to wear to measure respirable fraction (Walton and Vincent, 1998). The respirable cyclone as a personal sampler uses a cyclone, a personal sampling pump, and a filter with a cassette filter holder (NIOSH 0600).

There are possible problems sampling with a respirable cyclone: if the flow rate of the pump changes more than 5% then a representative sample has not been collected of the surroundings, and if dust is emitted in a specific direction the sampler might have to be moved out of that direction (Cherrie et al., 2010). There are also problems with filter bypass leakage if the cassettes are not sealed correctly (Baron and Bennett, 2002a; Baron et al., 2002b).

1.5.2 Passive sampling of particles

Passive sampling of particles entails sampling without any power supply. Passive samplers are constructed to be small and lightweight, which makes it easier to sample in inaccessible locations where lots of instruments cannot be brought along. During the years, passive samplers have been developed and tried for stationary sampling and personal sampling. Brown et al. (1994a,b, 1995) developed
one of the first passive dust samplers using an electret (a material with a permanent positive charge on one side and a permanent negative charge on the other). Brown et al. (1995) did a field trial of the sampler in metal processing industries comparing concentrations of the passive sampler with the IOM sampler and the respirable cyclone. In 1996, Vinzents also developed a passive personal dust monitor, this time using sticky foils. A field test was run in four different industries with different kinds of particle composition. The results from the sampler were compared with millipore field monitor (total dust) and IOM sampler. The particle size distribution of the sampler from wind tests was compared with the particle size distribution from an aerodynamic particle sizer (APS). Wagner and Leith (2001b,c) created the University of North Carolina passive aerosol sampler (UNC sampler) in 2001 (Wagner and Leith, 2001d). The UNC sampler, which was the only passive sampler used in the studies presented within this thesis, will be further explored in Section 1.6.

Yamamoto et al. (2006, 2007) created a passive aeroallergen sampler for aeroallergen particles between 10–100 µm, with a protective holder that can be hung around the neck for personal sampling, analysed with light microscopy. Ferm et al. (2006) and Ferm (2010) created passive samplers with filters for fine and larger particles to be able to study deposited particles. Different directions of the deposition surface for cylindrical and horizontal samplers were analysed by weighing and ion chromatography. For ambient PM, Lin et al. (2011) constructed a directional passive air sampler with a circular sampling tray consisting of open angular outlets. Einstein et al. (2012) developed the Einstein-Lioy deposition sampler to improve on other passive samplers. This sampler consists of a circular base that can house four filters and is analysed by polarised light microscopy and X-ray fluorescence. Another passive method was used for indoor measurements by Canha et al. (2014). They used a tray with filters in open petri dishes. Arnoldsson et al. (2015) developed a passive sampler for polycyclic aromatic hydrocarbons (PAHs) and oxygenated PAHs analysed by mass spectrometry, and has also been evaluated in the field (Magnusson et al., 2016).

Problems with passive sampling of particles have not been reported to the same extent as for i.a. respirable cyclones.

1.6 The UNC sampler

The UNC sampler is a passive aerosol sampler created by Wagner and Leith (2001b,c) and modified by Ott et al. (2008b). The UNC sampler consists of a scanning electron microscopy (SEM) pin stub, a collection surface, an 18 mm mesh cap with a 6.35 mm circular opening fastened with two screws to the SEM stub, and a thin
mesh adhered to the top (Fig. 1.3). The UNC sampler is in a protective holder when it is not used.

The UNC sampler collects particles by gravitational settling and diffusion. The limit of the biggest particle diameter the UNC sampler collects is determined by the mesh hole size. The mesh cap also protects the sampler from deposition of bigger particles, e.g. hair and debris. The mesh used in the studies presented within this thesis (Fig. 1.3e) had 150 µm holes (diameter of conical hole opening, with smaller opening diameter at top). Ott and Peters (2008a) created a shelter for UNC samplers to protect them from precipitation and wind effects during measurements.

1.6.1 Theory of the UNC sampler

The particles deposited on the collection surface of the UNC sampler are, as mentioned before, deposited by gravitational settling and diffusion. For the larger particle mass concentrations (PM$_{2.5}$, respirable fraction, PM$_{10-2.5}$, and PM$_{10}$) the deposition model is solely based on gravitational settling. For ultrafine particles Nash and Leith (2010) developed a deposition model based on diffusion as well. The deposition model presented here is the Wagner and Leith (2001b) model. It relies on microscopic imaging of the collection surface. The imaged particles are then converted to relevant exposure assessment quantities, e.g. mass concentration and particle size distribution.

In the Wagner and Leith deposition model the contribution of a single particle,
i, to mass concentration, $C$, is defined as

$$C_i = \frac{j_{m,i}}{v_{\text{dep},i}} = \left( \frac{m_i}{A_T t} \right) \frac{1}{v_{\text{dep},i}},$$  \hspace{1cm} (1.7)

where $j_{m,i}$ is the mass flux of the particle (particle mass per time per substrate area imaged), $v_{\text{dep},i}$ is the deposition velocity of the particle, $m_i$ is the mass of the particle, $A_T$ is the total area of the sampler that was imaged, and $t$ is the duration of sampling.

For wind speeds in a majority of indoor environments and some outdoor environments, the deposition velocity takes on the simple form

$$v_{\text{dep}} = v_{ts} \gamma_{\text{mesh}},$$  \hspace{1cm} (1.8)

where $\gamma_{\text{mesh}}$ is the mesh factor, an empirical modifier to account for the presence of the mesh cap, and the form of $v_{ts}$ is known from Eqn. (1.6).

Accounting for the fact that the UNC sampler analysis model is based on microscopic imaging of the particles, the aerodynamic diameter is replaced by the projected area diameter, $d_{pa}$, which is the diameter of a circle having the same projected area, $A$, as the particle,

$$d_{pa} = \sqrt{\frac{4A}{\pi}}.$$  \hspace{1cm} (1.9)

The relationships between the aerodynamic diameter and the projected area diameter are defined as

$$d_{ev} = \frac{d_{pa}}{S_v},$$  \hspace{1cm} (1.10)

$$d_a = d_{ev} \left( \frac{\rho_p C_{c,dev} \rho_0 C_{c,da}}{S_d} \right)^{1/2},$$  \hspace{1cm} (1.11)

where $S_d$ is the dynamic shape factor, $S_v$ is the volume shape factor, $d_{ev}$ is the equivalent volume diameter (the diameter of a sphere with the same volume as the volume of the irregular particle), and $\rho_p$ is the particle density.

By inserting Eqns. (1.6), (1.8), (1.10), and (1.11) in Eqn. (1.7) the final form of the particle concentration becomes

$$C_i = \frac{3\pi \eta S_d}{\gamma_{\text{mesh},i} S_v C_{c,dev} A_T t} d_{pa,i},$$  \hspace{1cm} (1.12)

where $C_{c,dev}$ is the Cunningham slip correction factor for a particle with diameter $d_{ev}$.
1.6.2 Overview of UNC sampler studies

From the time the UNC sampler was created and patented in 2001 there have been several studies in which the UNC sampler has been used for stationary sampling. A majority of the studies are presented in Table 1.1. At first the studies pertaining the UNC sampler were focused on comparing the particle mass concentrations of the UNC sampler with other sampling instruments (Wagner and Leith, 2001a; Wagner and Macher, 2003). Ott and Peters (2008a) proceeded with creating a shelter for the UNC sampler for protection against the elements. In recent studies the focus from the concentration comparisons of the UNC sampler has been shifted to the classification of particle composition and capturing the spatial variability with the UNC sampler (Sawvel et al., 2015; Byeon et al., 2015; Shen et al., 2016; Peters et al., 2016). There has only been one study where the UNC sampler was used in a working environment (Wagner and Leith, 2001a).

In the first study in a working environment by Wagner and Leith (2001a), they found that there was a good correlation for PM$_{10}$ and PM$_{2.5}$ between the UNC samplers and the cascade impactors. The particle size distributions also looked fairly similar in shape. Wagner and Macher (2003) saw that there were generally good correlations between the UNC samplers and the different active samplers, and worse precision for the UNC samplers when there were lower particle counts. The particle size distributions between the UNC samplers and the personal impactor exhibited discrepancies. Ott and Peters (2008a) found that flat plates, to protect the UNC sampler from precipitation, could be used and still lead to high correlation for UNC sampler measurements compared to dichotomous sampler measurements for PM$_{10-2.5}$. In another study, Ott et al. (2008b) found similar results in that the correlation was high between the UNC sampler and dichotomous sampler, but that the UNC sampler measurements deviated 29% from the dichotomous sampler measurements.

Ott et al. (2008c) and Wagner et al. (2012) studied spatial variability and found heterogeneity in concentrations when measuring at different locations on the same site compared to centrally located stations and air quality monitoring networks. Ott et al. (2008c) stated that the implications from their findings could benefit exposure assessments in epidemiological studies. Leith et al. (2007) and Peters et al. (2016) found that measured PM$_{10-2.5}$ agreed well for UNC samplers compared with federal reference method (FRM) samplers, and Leith et al. (2007) also found that the particle size distributions for the UNC sampler compared with an APS showed similar distributions. Wagner and Casuccio (2014) also found good agreement between UNC sampler results and FRM sampler results for PM$_{10}$ and PM$_{2.5}$.
Table 1.1: Overview of several studies focused on the UNC sampler. Ranging from the first study in 2001 to studies in 2016. All studies on the UNC sampler have not been included. When the information is missing the entry is represented by a '-'.

<table>
<thead>
<tr>
<th>Particle size fraction</th>
<th>Particle type</th>
<th>Location</th>
<th>Compared with</th>
<th>Shelter</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM&lt;sub&gt;2.5&lt;/sub&gt;, PM&lt;sub&gt;10&lt;/sub&gt;</td>
<td>Sand, CaMg(CO&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;, Na&lt;sub&gt;2&lt;/sub&gt;CO&lt;sub&gt;3&lt;/sub&gt;, CaO</td>
<td>Glass manufacturing plant</td>
<td>Andersen impactor</td>
<td>No</td>
<td>Wagner and Leith (2001a)</td>
</tr>
<tr>
<td>PM&lt;sub&gt;2.5&lt;/sub&gt;, respirable, PM&lt;sub&gt;10−2.5&lt;/sub&gt;, PM&lt;sub&gt;10&lt;/sub&gt;</td>
<td>Heterogeneous aerosols</td>
<td>Residences</td>
<td>GS Cyclone, MS&amp;T Impactor, Marple personal cascade impactor</td>
<td>No</td>
<td>Wagner and Macher (2003)&lt;sup&gt;†&lt;/sup&gt;</td>
</tr>
<tr>
<td>PM&lt;sub&gt;10−2.5&lt;/sub&gt;</td>
<td>Inorganic dust, inorganic and organic particles (heterogeneous aerosols)</td>
<td>Outdoor sites</td>
<td>Federal reference method</td>
<td>No</td>
<td>Leith et al. (2007)</td>
</tr>
<tr>
<td>PM&lt;sub&gt;10−2.5&lt;/sub&gt;</td>
<td>Road dust (laboratory), heterogeneous aerosols (sites)</td>
<td>Laboratory and outdoor sites</td>
<td>Dichotomous sampler</td>
<td>Yes</td>
<td>Ott and Peters (2008a)&lt;sup&gt;†&lt;/sup&gt;</td>
</tr>
<tr>
<td>PM&lt;sub&gt;10−2.5&lt;/sub&gt;</td>
<td>Road dust (laboratory), heterogeneous aerosols (sites)</td>
<td>Laboratory and outdoor sites</td>
<td>Dichotomous sampler</td>
<td>Yes</td>
<td>Ott et al. (2008b)&lt;sup&gt;†&lt;/sup&gt;</td>
</tr>
<tr>
<td>PM&lt;sub&gt;10−2.5&lt;/sub&gt;</td>
<td>Heterogeneous aerosols</td>
<td>Outdoor sites</td>
<td>Optical particle counter</td>
<td>Yes</td>
<td>Ott et al. (2008c)&lt;sup&gt;†&lt;/sup&gt;</td>
</tr>
<tr>
<td>PM&lt;sub&gt;10−2.5&lt;/sub&gt;</td>
<td>Glass beads, limestone, titanium dioxide</td>
<td>Laboratory</td>
<td>Dichotomous sampler, Aerodynamic particle sizer</td>
<td>No</td>
<td>Whitehead and Leith (2008)</td>
</tr>
<tr>
<td>PM&lt;sub&gt;7−2.5&lt;/sub&gt;</td>
<td>-</td>
<td>Laboratory and outdoor sites</td>
<td>Dusttrak, federal reference method</td>
<td>Yes</td>
<td>Assael et al. (2010)*</td>
</tr>
<tr>
<td>Ultrafine</td>
<td>Ammonium fluorescein</td>
<td>Laboratory</td>
<td>Scanning mobility particle sizer</td>
<td>No</td>
<td>Nash and Leith (2010)</td>
</tr>
<tr>
<td>PM&lt;sub&gt;10−2.5&lt;/sub&gt;</td>
<td>Road dust, biological, salt, chromium-rich, carbonaceous road dust</td>
<td>Outdoor sites</td>
<td>-</td>
<td>Yes</td>
<td>Lagudu et al. (2011)&lt;sup&gt;†&lt;/sup&gt;</td>
</tr>
<tr>
<td>PM&lt;sub&gt;10−2.5&lt;/sub&gt;</td>
<td>Road dust, biological, salt, gypsum, carbonaceous road dust</td>
<td>Outdoor sites</td>
<td>-</td>
<td>Yes</td>
<td>Kumar et al. (2012)&lt;sup&gt;†&lt;/sup&gt;</td>
</tr>
<tr>
<td>PM&lt;sub&gt;2.5&lt;/sub&gt;, PM&lt;sub&gt;10−2.5&lt;/sub&gt;, PM&lt;sub&gt;10&lt;/sub&gt;</td>
<td>Bermuda grass burn particles</td>
<td>Outdoor sites</td>
<td>E-BAM</td>
<td>Yes</td>
<td>Wagner et al. (2012)&lt;sup&gt;†&lt;/sup&gt;</td>
</tr>
<tr>
<td>Particle fraction</td>
<td>Particle type</td>
<td>Location</td>
<td>Compared with</td>
<td>Shelter</td>
<td>Reference</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------</td>
<td>----------</td>
<td>---------------</td>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>PM$_{10-2.5}$</td>
<td>Iron-containing particles (fly ash, mineral dust, NaCl agglomerates, Ca-S agglomerates)</td>
<td>Outdoor sites</td>
<td>-</td>
<td>Yes</td>
<td>Ault et al. (2012)$^\dagger$</td>
</tr>
<tr>
<td>PM$<em>{2.5}$, PM$</em>{10-2.5}$</td>
<td>-</td>
<td>Residences and outdoor sites</td>
<td>-</td>
<td>Yes</td>
<td>Arashiro and Leith (2013)</td>
</tr>
<tr>
<td>PM$<em>{2.5}$, PM$</em>{10-2.5}$, PM$_{10}$</td>
<td>Crustal material</td>
<td>Outdoor sites</td>
<td>Federal reference method</td>
<td>-</td>
<td>Wagner and Casuccio (2014)$^\dagger$</td>
</tr>
<tr>
<td>Ultrafine, PM$<em>{2.5}$, PM$</em>{10-2.5}$, PM$_{10}$</td>
<td>Al, Ba, Ca, C, Cl, Cr, Cu, Fe, Pb, Mg, Mn, Ni, P, Si, Na, S, Ti, Zn</td>
<td>Residences and outdoor sites</td>
<td>-</td>
<td>Yes</td>
<td>Funk et al. (2014)$^\dagger$</td>
</tr>
<tr>
<td>PM$_{10-2.5}$</td>
<td>Pollen, C-rich, NaCl, Na-rich, Ca/S-rich, Fe-oxide, Si/Al-rich, Al-rich, Si-rich, Metal-rich, Fe-rich, Ca-rich</td>
<td>Outdoor sites</td>
<td>-</td>
<td>Yes</td>
<td>Sawvel et al. (2015)$^\dagger$</td>
</tr>
<tr>
<td>PM$<em>{2.5-1.0}$, PM$</em>{10-2.5}$</td>
<td>Soil/road dust, iron-rich, carbonaceous, aluminium, secondary nitrates/sulphates</td>
<td>Outdoor sites and subway</td>
<td>-</td>
<td>Yes</td>
<td>Byeon et al. (2015)$^\dagger$</td>
</tr>
<tr>
<td>PM$<em>{2.5}$, PM$</em>{10-2.5}$, PM$_{10}$</td>
<td>Lead-rich</td>
<td>Outdoor sites and balconies</td>
<td>-</td>
<td>Yes</td>
<td>Shen et al. (2016)$^\dagger$</td>
</tr>
<tr>
<td>PM$_{10-2.5}$</td>
<td>Pollen, stainless steel, Fe-oxide, metal-rich, Fe-rich, Ca-rich, Si-rich, Ca/Si, Cu/S, Al-rich, Si/Al, NaCl, Na-rich, C-rich</td>
<td>Outdoor sites</td>
<td>Federal reference method</td>
<td>Yes</td>
<td>Peters et al. (2016)$^\dagger$</td>
</tr>
</tbody>
</table>

$^\dagger$Calculations for PM$_{10-2.5}$ concentrations have not been stated, or have not followed conventional PM$_{10-2.5}$ concentration calculations.

$^\ast$The shelter differed in this study from Ott and Peters (2008a), and the UNC sampler was part of an outdoor measurement construction.
1.7 Passive sampling for occupational dust exposure

Passive sampling, both for stationary and personal measurements, has been proven to work and is currently used for gaseous compounds by using e.g. diffusion samplers (Durrani and Ilić, 1997; Cyrys et al., 2012; Hagenbjörk-Gustafsson et al., 2014). Passive sampling for occupational particle exposure has been investigated before, but the methods used were too complicated for simple use (Brown et al., 1995; Vinzents, 1996; Schneider et al., 2002).

In a study comparing active and passive air sampling monitors Nothstein et al. (2000) concluded that passive samplers were more cost-effective than active samplers. The passive sampling resulted in lower labour costs and cheaper samplers. However, Nothstein et al. (2000) did note that validation (evaluation of method in accordance with established protocols and criteria) was more often needed for passive samplers compared with active samplers. Although, Nothstein et al. (2000) also noted that passive samplers were less intrusive. A problem when measuring occupational exposure is that workers, at times, find the instruments loud and bulky (Cherrie et al., 1994). Thus, the aspiration to find a passive personal sampler for occupational exposure lies not only in the benefits of a cost-effective instrument, but the unobtrusiveness of it. The passive sampler would then not only be suitable for personal sampling, but also to measure the spatial variability in concentration at the different locations in the working environment.

We chose to use the UNC sampler because: it is the smallest passive sampler with protection; it is commercially available; previous studies have shown consistency with recognised measurement methods; analysis yields i.a. mass concentration, particle size distribution, and particle composition. The UNC sampler has only been used in a working environment once, for a small field study (Wagner and Leith, 2001a). The UNC sampler has never been used as a personal sampler. Thus, there is a lack of knowledge concerning use of the UNC sampler to measure occupational exposure. A first step to gain more knowledge about the UNC sampler in working environments is to use the UNC sampler as it has been used before, with stationary sampling, but in a working environment. After it is known how the UNC sampler behaves in a working environment compared to already established sampling instruments, one can continue to test it for use as a personal sampler of occupational dust exposure. One such working environment with occupational dust exposure problems is the mine (Hearl and Hewett, 1993; Walton and Vincent, 1998). There are several health effects affecting miners with occupational dust exposure, e.g. higher risk for lung cancer, gastric cancer, silicosis, bronchitis, chronic obstructive pulmonary disease, and airway inflammation (Ji and Hemminki, 2006; Ådelroth et al., 2006; Bergdahl et al., 2010; Jonsson et al., 2010; Elgstrand and
1.7. PASSIVE SAMPLING FOR OCCUPATIONAL DUST EXPOSURE

Vingård, 2013; Lee et al., 2016; Poinen-Rughooputh et al., 2016). Thus, the working environment chosen to study the UNC sampler in was a mine and the focus was the respirable fraction of inorganic dust. The occupational exposure limit (OEL) for the respirable fraction of inorganic dust is $5 \text{ mg m}^{-3}$ for a workday, normally eight hours, in Sweden (AFS 2015:7).
Chapter 2

Aims

The overall purpose was to develop more knowledge about the UNC sampler and the possibility of using it for personal sampling of occupational dust exposure. The specific aims were to:

• Characterise the stationary performance of the UNC sampler in the working environment of an open pit mine.

• Evaluate and possibly improve the UNC sampler for stationary sampling in the working environment of an open pit mine and compare the UNC sampler with commonly used aerosol sampling methods.

• Characterise the impairment in performance of the UNC sampler concentrations when decreasing the number of images in order to achieve lowered costs and decreased analysis time.

• Establish if the UNC sampler could be used for personal sampling in the working environment of an open pit mine.
Chapter 3

Materials and Methods

During three consecutive years, in the same season, measurements with UNC samplers and active samplers were made in an open pit mine. Two of the measurement campaigns were based on stationary sampling, while the third was personal sampling of the workers. Details for the first two measurement campaigns can be found in Papers I and II, and for the personal sampling in Paper IV. For the non-invasive personal sampling, ethical approval was given by the regional ethical review board in Umeå (Dnr 2012-365-31M). The sampling locations were the crushing station, drive station, concentrator, and concentrate terminal, in order to cover various different exposure levels. There were no workers from the concentrate terminal included in the personal sampling campaign. There were filter blanks for the impactors and cyclones, UNC sampler transport blanks, and UNC sampler field blanks for the measurement campaigns. The particle density used for Papers II, III, and IV was 2.8 g cm$^{-3}$ (crushing station, drive station, and concentrator) and 3.75 g cm$^{-3}$ (concentrate terminal). For Paper I the particle density was set to 2.0 g cm$^{-3}$.

3.1 The mining process

The mining process consists of several different stages (Fig. 3.1). The ore is loaded and transported on trucks after blasting to the crushing station, where the ore is crushed. After crushing the ore is transported on conveyor belts through drive stations towards the concentrator. At the concentrator the ore goes through several steps and is purified and dewatered resulting in the end material, ore concentrate. The ore concentrate is transported to the concentrate terminal, where the concen-
trate is stored short-term and loaded onto rail wagons for transport to a smelter.

The different locations were scouted and chosen because the locations differed in concentration range, particle size, and exposure consisted mostly of inorganic mineral dust without interference of other types of particles, e.g. exhaust particles from the trucks.

![Image](image.png)

Figure 3.1: Schematic overview of the mining process for the purification of the ore to concentrate.

### 3.2 First stationary sampling in the mine

The first measurement campaign consisted of ten UNC samplers with polycarbonate (PC) collection surface and ten UNC samplers with carbon tab (CT) collection surface at each location. The PC UNC samplers were bought from and assembled by RJ LeeGroup (Monroeville, PA, USA). The CT UNC samplers were assembled in-house in an ISO class 6 cleanroom. At each location the measurement started with one PM$_{2.5}$ impactor (SKC impact sampler PM$_{2.5}$), one PM$_{10}$ impactor (SKC impact sampler PM$_{10}$), six PC and six CT UNC samplers (Paper I, Fig. 1). After
3.3. SECOND STATIONARY SAMPLING IN THE MINE

eight hours two PC and two CT UNC samplers were removed and replaced with
two new ones of each type. After another eight hours (16 hours in total), the two
PC and two CT UNC samplers running for 16 hours were removed, and the two
PC and two CT UNC samplers running for eight hours were removed and replaced
with two new ones of each type. After another eight hours (24 hours in total), all
of the samplers were removed. Thus, all of the UNC sampler measurements were
recalculated to time-averaged means of the concentrations to be able to compare
them with the 24 hours impactor results.

During 15 min at the start and 15 min at the end of sampling at each location
a Lighthouse HH 3016-IAQ particle counter measuring particles with an aerody-
namic diameter of 0.3–10 µm was also used to estimate the percentage of particle
mass potentially undetected in the microscope below 0.75 µm.

3.3 Second stationary sampling in the mine

The second measurement campaign consisted of ten CT UNC samplers, three
PM$_{2.5}$ impactors, three PM$_{10}$ impactors, three respirable aluminium cyclones, and
one aerodynamic particle sizer (APS, TSI Model 3321 range 0.5–20 µm) at each
location and time (evening, night, and morning). The CT UNC samplers were as-
sembled in-house in an ISO class 6 cleanroom. Each measurement took approxim-
ately eight hours spanning a total of 24 hours at each location. The pre-calibrated
APS was used as a reference, to compare the shape of the particle size distributions
from the UNC samplers to that of the APS. The APS sampled continuously, with
20 s intervals, at each location and time.

3.4 Personal sampling with the UNC sampler

For the personal sampling of respirable fraction nine measurement sets were made
(Paper IV, Table 1). Each measurement set consisted of two PC UNC samplers and
one respirable cyclone fastened to the worker’s clothing (Paper IV, Fig. 1). The
PC UNC samplers were bought from, and assembled by, RJ LeeGroup (Monro-
eville, PA, USA). Chronologically, measurement campaign three was the first one
conducted, but the data was not possible to interpret until after Papers I and II.
CHAPTER 3. MATERIALS AND METHODS

3.5 Active samplers with filters

Setup and analysis of the active samplers have been described in detail in Papers I, II, and IV. The filters were weighed twice, before and after sampling. The impact samplers had pre-oiled impaction discs to reduce particle bounce. The flow rate for the impact samplers was 10 L min$^{-1}$ and 2.5 L min$^{-1}$ for the respirable cyclone. For chemical composition, X-ray diffraction (XRD) analysis was made on the impactor filters from the second measurement campaign, one for PM$_{10}$ and one for PM$_{2.5}$, from each location.

3.6 Analysis of the UNC sampler

The UNC samplers from the different measurement campaigns were analysed with a scanning electron microscope (SEM). The UNC samplers from measurement campaign 2 and 3 were also analysed with energy dispersive X-ray spectroscopy (EDS). The samplers from the first measurement campaign were analysed with a Philips XL30 environmental SEM D1079 with a solid state backscatter detector with $\times$100 magnification. Depending on the type of collection surface, 16–44 images were collected to cover the whole surface. The SEM consisted of a manual stage with knobs for moving the sample, thus each image was collected manually.

The UNC samplers from the second measurement campaign were analysed with an angle-selective backscatter detector in the Carl Zeiss MERLIN FE-SEM GEMINI II. For the image collection for the samplers a $\times$500 magnification was used and 60 images were collected covering 51% of the collection surface. Each image was collected manually, but the stage was controlled by software and no manual rotation of knobs was needed. To be able to compare the difference in concentration due to the effect of magnification on smaller particles a $\times$3000 magnification was also used on 12 samplers (three from each location). For one sampler 81 images were collected with $\times$3000 magnification to cover one image with $\times$500 magnification.

The UNC samplers from the third measurement campaign were analysed with a backscatter electron detector in the Carl Zeiss EVO LS15 SEM and an EDS detector (Oxford Instruments X-Max$^\text{N}$ 80 mm$^2$) for elemental analysis of the particles. The image collection was automatic by defining a pre-defined area in the SEM software, using the entire collection surface of each UNC sampler. A minimum of 192 images were taken with $\times$500 magnification.

After image collection, the image processing was done with a macro we wrote in ImageJ (Version 1.48, National Institutes of Health, USA, released 2014). After processing, every single image was investigated visually and when the primary
thresholding did not cover the particles the method was changed to the triangle method.

![Image](image.png)

Figure 3.2: An example of how particles from one image are detected and accounted for.

The resulting text files from ImageJ were in turn processed with different functions written in MATLAB [R2014b (8.4.0.150421), The MathWorks, Inc., Natick, MA, USA, released 2014] to obtain the concentrations and particle size distributions. For respirable fraction, and comparison with PM$_{2.5}$ and PM$_{10}$ impactor concentrations, the sampling criteria for each particle size fraction were applied to the UNC sampler concentration calculations. The sampling criteria are presented in Hinds (1999) Eqns. (Hinds 11.13), (Hinds 11.19), and (Hinds 11.20). All of the concentrations were blank corrected, except for the UNC samplers from the personal sampling.

### 3.7 Changes to the UNC sampler model

Since the wind speed in all measurement locations was registered at 0 m s$^{-1}$ we decided to modify the Wagner and Leith deposition model. The mesh factor was changed into what we call an area factor that only accounts for the open area of the mesh. The open area of round holes and triangular pitch (Fig. 3.3) is stated by
CHAPTER 3. MATERIALS AND METHODS

RMIG (2018) as

$$\text{Open area} = 90.69 \frac{D^2}{P^2},$$  \hspace{1cm} (3.1)

where D is the hole size (diameter) in mm and P is the pitch in mm. The pitch is the length of the side of a triangle formed by three holes, measured from the centre of one hole to the other. Using the formula resulted in open area equal to 0.27, which was consistent with the specification sheet for the UNC sampler. Thus, the area factor for our mesh was equal to 0.27.

![SEM Image of Mesh](image_url)

Figure 3.3: SEM image of the mesh with the mesh holes clearly visible. D is the hole size and P is the pitch.

3.8 Modifications of the UNC sampler

When the UNC sampler is not being used for sampling it is housed in a protective holder. After the first stationary sampling measurement campaign we changed the protective holders to bigger ones (Fig. 3.4). This was because there were difficulties extracting the UNC sampler from the smaller holder, due to unwanted effects of cold affecting the fingers.
3.8. MODIFICATIONS OF THE UNC SAMPLER

Figure 3.4: UNC sampler protective holders. The left one is bigger than the right one, but the UNC sampler is removed more easily from the bigger one.

For the first stationary sampling we used UNC samplers with different collection surfaces; polycarbonate filter and carbon tab (Fig. 3.5a and b). The carbon tab adhered a bit to the closed area of the mesh cap, thus for the second stationary sampling we punched out 8 mm of the backing material on the carbon tab and kept the rest as a ring around it to keep it from adhering to the mesh cap (Fig. 3.5c).

Figure 3.5: Different UNC sampler collection surfaces. (a) Polycarbonate filter. (b) Carbon tab. (c) Carbon tab with backing material.

For the stationary sampling we grounded the UNC samplers (Fig. 3.6). On all of the bottom plates of the protective shelters we drilled a hole and attached a power cord. The rubber grommet, which the UNC sampler was placed in, was covered with copper tape.
CHAPTER 3. MATERIALS AND METHODS

Figure 3.6: Bottom plate of the protective shelter with copper tape on the top and bottom of each rubber grommet. The fastened power cord is also visible at the bottom left.
3.9  Impairment in performance

To be able to characterise the impairment in performance of the UNC sampler concentrations, when decreasing the number of images, analyses were made in R (R Core Team, 2017, version 3.3.3, R Foundation for Statistical Computing, Vienna, Austria, released 2017). From the second measurement campaign, the samplers from drive station, concentrator, and concentrate terminal were used. For the 88 UNC samplers their corresponding images were varied between choosing 1 to 59 images. Bootstrapping was made with 1 000 different combinations for each number of images, sampled without replacement, yielding the within-sampler coefficient of variation ($CV_{ws}$). Thus, by knowing the corresponding $CV_{ws}$ for each number of images, the impairment to the overall coefficient of variation (CV) of the UNC sampler could be evaluated.

3.10  Statistics

For the second stationary measurement campaign to compare the UNC sampler to the other instruments (PM$_{10}$ impactor, respirable cyclone, and PM$_{2.5}$ impactor) a linear regression model was fitted with forced intercept through zero using OriginPro (OriginLab, version 8.0724, Northampton, MA, USA). All of the other analyses were made using (R Core Team, 2016, version 3.3.2, R Foundation for Statistical Computing, Vienna, Austria, released 2016). The analyses were descriptive statistics, t-Tests between mean concentrations for the UNC sampler versus the other instruments, and between the different UNC sampler models. For each measurement device a linear mixed effects model was fitted using the R package lme4 (Bates et al., 2014). The dependent variable in the model was particle size fraction concentration, the independent variables were location (consisting of 4 levels: crushing station, drive station, concentrator, and concentrate terminal) and time (consisting of 3 levels: evening, night, morning), and the random effect accounted for different mean concentrations at each of the 12 measurement occasions (location and time). From the mixed effects models the intraclass correlations (ICCs) and within occasion variances could, among other things, be determined.

For the personal sampling, means, standard deviations, and correlation coefficients were calculated using R (R Core Team, 2017, version 3.3.3, R Foundation for Statistical Computing, Vienna, Austria, released 2017) for the UNC samplers and respirable cyclones.
Chapter 4

Results

All of the presented results have been sampled from the working environment of an open pit mine. During all of the stationary sampling measurements the wind speed was registered at 0 m s$^{-1}$. It was snowing for a few hours during the sampling at the crushing station in the second measurement campaign.

4.1 The performance of the UNC sampler

The measurements from the first stationary sampling using the original analysis model with mesh factor exhibited underestimation for the UNC sampler compared with the impactors (Fig. 4.1). The UNC sampler with PC showed 24% and CT 35% of the impactor result for PM$_{2.5}$ (Figs. 4.1c and d). For PM$_{10}$, it was 39% with PC and 58% with CT of the impactor result (Figs. 4.1a and b).
CHAPTER 4. RESULTS

Figure 4.1: Modified figure from Paper I. UNC sampler with mesh factor versus impactor concentrations. (a) Polycarbonate PM$_{10}$. (b) Carbon tab PM$_{10}$. (c) Polycarbonate PM$_{2.5}$. (d) Carbon tab PM$_{2.5}$.

4.2 Evaluation and improvement of the UNC sampler

For the second stationary sampling campaign the original analysis model with mesh factor still showed an underestimation compared to the impactors. The UNC sampler with mesh factor showed 14% of the PM$_{2.5}$ impactor concentrations (Fig. 4.2).
4.2. EVALUATION AND IMPROVEMENT OF THE UNC SAMPLER

Figure 4.2: Modified figure from Paper II. Particle mass concentrations for the UNC sampler with mesh factor versus PM$_{10}$ impactor, respirable cyclone, and PM$_{2.5}$ impactor. The grey dots are each individual observation from the samplers and the black cross is the mean for both samplers. The value of the slope of the fitted linear regression model and R-squared are noted for each analysis model and particle mass concentration. (a) UNC sampler with mesh factor versus PM$_{10}$ impactor. (b) UNC sampler with mesh factor versus respirable cyclone. (c) UNC sampler with mesh factor versus PM$_{2.5}$ impactor.

Changing the UNC sampler model, by replacing the mesh factor with an area factor, resulted in particle size distributions that resembled those obtained by the APS, as opposed to the particle size distributions of the original mesh factor model (Fig. 4.3).
CHAPTER 4. RESULTS

Figure 4.3: Modified figure from Paper II. Normalised mass concentration distributions ($dM/d\log d_a$) for the UNC sampler with mesh factor and area factor versus APS at the different locations. Note the shape of the different distributions with respect to the chosen model compared to the APS. Crushing station: (a) mesh factor; (b) area factor. Drive station: (c) mesh factor; (d) area factor. Concentrator: (e) mesh factor; (f) area factor. Concentrate terminal: (g) mesh factor; (h) area factor.
4.2. EVALUATION AND IMPROVEMENT OF THE UNC SAMPLER

Redoing the mass concentration calculations for the UNC sampler with the area factor led to less underestimation for the UNC sampler compared with the impactors (Fig. 4.4).

Figure 4.4: Modified figure from Paper II. Particle mass concentrations for the UNC sampler with area factor versus PM$_{10}$ impactor, respirable cyclone, and PM$_{2.5}$ impactor. The grey dots are each individual observation from the samplers and the black cross is the mean for both samplers. The value of the slope of the fitted linear regression model and R-squared are noted for each analysis model and particle mass concentration. (a) UNC sampler with area factor versus PM$_{10}$ impactor. (b) UNC sampler with area factor versus respirable cyclone. (c) UNC sampler with area factor versus PM$_{2.5}$ impactor.
Adjusting for microscope resolution, by changing the magnification from ×500 to ×3000, led to an additional increase in mass concentration. For the area factor model the concentrations increased with a mean factor of 2.44 ± 0.54 times for PM$_{2.5}$ (calculated from nine samplers, three from each indoor location). Adjusting all of the PM$_{2.5}$ mass concentrations for the UNC sampler with area factor with 2.44 led to a regression model slope of 1.07 compared to the PM$_{2.5}$ impactor (Fig. 4.5).

![Figure 4.5: UNC sampler with area factor versus PM$_{2.5}$ impactor when accounting for the magnification change from ×500 to ×3000.](image)

### 4.3 Characterising the impairment in performance

We investigated how much error was introduced by using fewer images than the collected 60 for the concentration calculations (Table 4.1). The within-sampler coefficient of variation (CV$_{ws}$) from 1 000 bootstrapped samples for respirable fraction was 8.26% for ten images (Table 4.1). With respect to rules for the image collection (based on the distance to the centre of the sampler) CV$_{ws}$ changed from 8.26% to 8.13% for ten images. Applying the CV$_{ws}$ to the overall CV of the UNC
4.4. PERSONAL SAMPLING WITH THE UNC SAMPLER

sampler, with CV derived from the mean and within occasion variance (Paper II, Table 2), led to an increase in CV from 36% to 37%.

Table 4.1: Modified table from Paper III. Descriptive statistics of within-sampler CV for 5, 10, 15, and 20 images from 1 000 bootstrapped samples for respirable fraction.

<table>
<thead>
<tr>
<th>CV_{ws} (%)</th>
<th>5 images</th>
<th>10 images</th>
<th>15 images</th>
<th>20 images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>4.70</td>
<td>3.20</td>
<td>2.50</td>
<td>2.00</td>
</tr>
<tr>
<td>Median</td>
<td>11.1</td>
<td>7.75</td>
<td>5.75</td>
<td>4.75</td>
</tr>
<tr>
<td>Mean</td>
<td>12.2</td>
<td>8.26</td>
<td>6.38</td>
<td>5.21</td>
</tr>
<tr>
<td>Max</td>
<td>40.87</td>
<td>27.8</td>
<td>21.9</td>
<td>17.7</td>
</tr>
</tbody>
</table>

4.4 Personal sampling with the UNC sampler

When the UNC sampler was used as a personal sampler the particles on the collection surface of the sampler were heterogeneously deposited (Fig. 4.6). There was a higher density ring of particles at the edge of the collection surface. Imaging showed particles shaped like gravel with an elemental composition expressing mineral origin. The particle size distributions when using area factor were reasonable (Fig. 4.7), but compared with the respirable cyclone concentrations the UNC sampler concentrations were approximately 30 times higher.
CHAPTER 4. RESULTS

Figure 4.6: The entire UNC sampler collection surface imaged with a SEM. The particles were deposited heterogeneously with a higher density of particles in a ring at the edge of the collection surface.

Figure 4.7: Modified figure from Paper IV. Normalised mass concentration distributions \( \frac{dM}{d\log d_a} \) for the UNC samplers calculated with (a) mesh factor and (b) area factor.
Chapter 5

Discussion

Before the presented studies, the UNC sampler had not been assessed for occupational dust exposure in a mine. For these studies we did three measurement campaigns in an open pit mine.

5.1 Interpretation of the main results

Since the UNC sampler had only once before been used in a working environment (Wagner and Leith, 2001a) we wanted to make a measurement campaign in the mine to compare the UNC sampler with established methods. In the first measurement campaign we characterised the stationary performance of the UNC sampler in the working environment. The UNC sampler underestimated the concentrations compared with impactors (PM$_{2.5}$ and PM$_{10}$, as seen in Fig. 4.1). The results from the Lighthouse particle counter could explain some degree of underestimation for the UNC sampler, but not all of the underestimation for both PM$_{2.5}$ and PM$_{10}$. Given the numerous studies, as seen in Table 1.1, showing agreeable results with established methods, we decided to conduct another measurement campaign including the respirable cyclone and an APS as well.

From the collected material during the second measurement campaign the UNC sampler was evaluated again. Once again the UNC sampler underestimated the concentrations compared with the PM$_{2.5}$ impactor (Fig. 4.2). Studying the particle size distributions of the UNC sampler and APS we saw that the distributions differed (Fig. 4.3). Particle size distributions as the ones from the APS have previously been reported for dust from similar environments (Gonzales et al., 2014; Chubb and Cauda, 2017). Those particle size distributions also had a mass median dia-
CHAPTER 5. DISCUSSION

The diameter at which 50% of the particles by mass are smaller and 50% are larger) below ten micrometres. This supports the notion that the particle size distribution obtained with the UNC sampler is incorrect for the original mesh factor model.

The original mesh factor model of the UNC sampler was based on wind tunnel experiments (Wagner and Leith, 2001b,c). There was no wind registered at the different locations in the mine, where our measurements took place. Thus, we tried modifying the Wagner and Leith deposition model by replacing the mesh factor with a factor, the area factor, based solely on the open area of the mesh. This led to an amplification of the mass contribution of the smaller particles and attenuation of the mass contribution of the larger particles compared to the original model. The new area factor model resulted in similar particle size distributions to that of the APS, and less underestimation compared with the PM$_{2.5}$ impactor (Figs. 4.3 and 4.4). The remaining underestimation could be explained by microscope limitations (low magnification) for the area factor model (Fig. 4.5). The underestimation for the mesh factor model could not be explained by the microscope limitations. Thus, the area factor model was selected as the model to be used in the mine for stationary sampling by the following reasons: similarities in particle size distributions; lower underestimation for PM$_{2.5}$, and; stronger correlation for the UNC sampler with the PM$_{10}$ impactor.

The ICCs for the UNC sampler and the comparison samplers were calculated to compare how well the samplers could differentiate between different concentration levels and how precise each group of parallel samplers were (ten UNC samplers, three cyclones, three PM$_{2.5}$ impactors, and three PM$_{10}$ impactors for each group). The UNC sampler compared with the respirable cyclone had a higher ICC, 0.51 versus 0.24 (Paper II, Table 2). Thus, compared to the established sampler for occupational respirable exposure the UNC sampler showed higher precision and better ability to distinguish between the different concentrations measured.

Furthermore, the within occasion variance was also higher for the respirable cyclone. Thus, for the UNC sampler there is still room for a trade-off between a loss in precision and e.g. decreased analysis time. One such trade-off could be the number of images needed from microscopic imaging for the concentration calculations of the UNC sampler. One of the strongest limitations of the UNC sampler is the time-consuming image collection with SEM. Investigating the effect of decreasing the number of images, we found that for ten images the overall CV changed from 36% to 37%. Hence, minimising the number of images needed from microscopic imaging for the concentration calculations could be done with a negligible loss in precision and would greatly improve the usability of the UNC sampler.
5.1. INTERPRETATION OF THE MAIN RESULTS

The third measurement campaign was made to test if the UNC sampler could be used for personal sampling instead of stationary sampling. The collected particles were indeed particles from the working environment and not other types of debris, e.g. skin or textile. Due to a person’s movements, the mesh factor model and area factor model were both investigated for personal sampling. The particle size distributions of the area factor model were similar to the distributions we had already seen with the APS, but the distributions from the mesh factor model were not (Fig. 4.7 compared to Fig. 4.3). Thus, for personal sampling in a mine we concluded that the area factor should be used.

The collection of particles from personal sampling with the UNC sampler showed heterogeneous deposition of particles, with a ring of particles near where the wall of the mesh cap had been (Fig. 4.6), as opposed to the homogeneous deposition obtained from stationary sampling. This could be due to grounding; for stationary sampling we grounded the samplers, and for personal sampling we did not. Wagner and Leith (2001b) did state that the sampler should be grounded when possible, but there has been no reports of the sampler ever being grounded in other studies. In the present study, the UNC sampler also showed approximately 30 times higher concentrations than the respirable sampler, with concentrations higher than the OEL at 5 mg m\(^{-3}\). Such high concentrations are perceived as rather uncomfortable and with clearly visible dust in the air. The exposure was obviously not that severe, based on visits to the locations. Hence, there was something affecting the UNC sampler when measuring on a person.

Personal sampling and stationary sampling differ in the sense that for personal sampling there is a moving person wearing the sampler. The sampler or it’s holder is constantly rubbed against the clothes of the worker. Particles may be attracted and in a sense sucked in to the UNC sampler if the sampler is charged by the rubbing and the particles close to the sampler are influenced by that charge due to electrostatic forces, leading to an excess of particles collected. There is also the ‘personal cloud’ around a person with a higher concentration of particles compared to the rest of the surrounding (Ferro et al., 2004; You et al., 2013; Licina et al., 2017). Hence, the ‘personal cloud’ could also contribute to the excess of particles sampled by the UNC sampler. Resuspended particles falling off the clothes due to movement could to a greater degree be sucked into the UNC sampler if it and the particles are oppositely charged.

Possible ways to solve the issues with the UNC sampler for personal sampling could be to change the position of the UNC sampler on the worker. In occupations where workers wear helmets the sampler could be mounted on top of the helmet. This would lead to removal of the rubbing element, no wall effect, and possible reduction of static electricity. Furthermore, changing the material of the UNC
sampler holder to metal instead of plastic could also reduce the build up of static electricity. This should be investigated further. Thus, the UNC sampler could be used for stationary sampling in the working environment of an open pit mine, but is not yet ready for personal sampling.

5.2 Limitations of the UNC sampler

Depending on the analysis model chosen for quantity calculations, limitations are introduced. The area factor model is biased against larger particles, due to the ratio between particle size to the mesh hole size (the size of the mesh hole will be perceived as smaller for a bigger particle). The mesh used in the presented studies had circular holes with a diameter of approximately 150 µm. For a 15 µm spherical particle the probability of passage through a square opening, with the same size as the mesh, would be 80% and for a 1.5 µm particle it would be 98% (Taggart, 1945). Non-spherical particles near the hole size will be most affected. This effect can be included in the model, but that has not been done, as it introduces a relatively small bias. In order to better reflect reality this limitation could be accounted for in the model since it is easily amended.

The first part of the analysis model, pertaining the image rules, also bias against larger particles. The rule is that if a particle touches a side of an image, the particle is not accounted for. When calculating number of particles it is easy to amend for this bias, e.g. by choosing two sides of an image where particles are never counted if they touch the side, but they are if they touch the other two sides. The problem is that image rules based on counting are not the same as image rules for area measurements. Imagine that an extremely large particle is touching a side, but the part that is touching the side that is counted is really small, then the area will not be accounted for correctly. As Russ and Neal (2017) stated, more complicated procedures are needed for area measurements than for particle counting. The simplest one would be to only account for a smaller area from all of the images, but then the total area analysed will be smaller. Thus, more images should be analysed to account for the smaller area if it is important to avoid increase in variation. The image rules used for the studies in this thesis would exclude about 5% of 10 µm particles and will be less for smaller particles, and can therefore not be perceived as a substantial limitation.

Analysing the images can in some cases be a subjective process. The threshold used to separate the particles from the background can react differently to agglomerated and aggregated particles. Therefore, it is up to the person’s perception to be able to distinguish which areas have been represented as an area of several different particles instead of one area for each particle. This can only be done by examining
5.3 Applicability for other dust exposures

In the studies presented within this thesis we examined inorganic mineral dust, from a mine. As seen in Table 1.1 the UNC sampler has been used for stationary sampling in various outdoor environments, covering particles with different compositions. The limiting factor for using the UNC sampler is when the images are analysed and if there are so many particles that they cannot be separated into singular particles. For other types of dust exposures, where the particles do not collect into a large chunk, the UNC sampler could be used for exposure assessments. One example of other types of dust associated with health effects are road particles, e.g. dust and wear and tear from cars (Meister et al., 2012; Amato et al., 2014). As we already saw in Table 1.1 there have been a few studies covering road dust.

Two examples of occupational dust exposures the UNC sampler could be used for are fungi fragments and wood dust. Lee and Liao (2014) investigated exposure of farmers to fungi fragments, which can lead to respiratory diseases, and found that the exposure is high. They found that the fungi fragments were bigger than 1.8 µm. Fungi fragments are easily seen in the SEM and have round and cylindrical shapes (Mensah-Attipoe et al., 2016). Wood dust, which also affects the health
among i.a. wood workers, carpenters, and cabinet workers (Alonso-Sardón et al., 2015), has already been studied by using image analysis for SEM images (Mazzoli and Favoni, 2012).

Another occupational dust exposure is flour dust, affecting i.a. flour mill workers (Prabhasankar et al., 2003; Meo, 2004; Khodadadi et al., 2011; Neghab et al., 2012). The flour dusts that Laurièbre et al. (2008) studied had a median diameter of 4 and 7 µm, and the particles were clearly visible in SEM images. Some of the flour particles seemed to fuse together, either by agglomeration or aggregation. Particles that fuse together into new bigger particles are simple to analyse, but particles that make up a bigger area (that should be processed as singular particles) are harder to differentiate. Thus, flour dust could be problematic for the UNC sampler.

Quartz is another harmful occupational dust to be exposed to, affecting i.a. miners and construction workers (Sjödahl et al., 2007; Lee et al., 2016). For the different types of crystalline silica; quartz, cristobalite, and tridymite there are specific OELs in Sweden (AFS 2015:7). One of the advantages of the respirable cyclone is that the filter is not only analysed for mass concentration, but the concentrations of quartz, cristobalite, and tridymite are also possible to attain. The UNC sampler analysed by EDS has no way of differentiating between particles containing silicon and oxygen. The EDS can detect the elemental composition of a particle, thus it can detect silicon (Si) and oxygen (O), but the molecular composition cannot be detected, neither can the different types of crystalline silica. Thus, due to the importance of quartz measurements in certain working environments for health effects, the UNC sampler cannot at this moment in time replace the respirable cyclone.

### 5.4 Possibilities with the UNC sampler

One should not forget that there is much to gain when established methods in occupational dust exposure are challenged. More research is needed to fine tune the UNC sampler’s analysis process of the images. A non-spherical particle is indeed not spherical, which is assumed in the model, but we keep forgetting the importance of what such a simple sampling method offers. With just one sampler, we can after analysis calculate the concentration of different particle size fractions, not only the inhalable and respirable fractions, but also e.g. PM$_{2.5}$, PM$_{10-2.5}$, and PM$_{10}$. The modelling for the concentration of the UNC sampler allows whichever particle curve of interest, it can be steep or follow the sampling criteria for the different particle size fractions. The probability that the mass of a large particle (that is not counted to the particle size fraction) contributes to the concentration is impossible with the UNC sampler. If the choice is particles below 15 µm then

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Answer to the Ultimate Question of Life, the Universe, and Everything
only particles below 15.0 µm will be in the calculations. In addition, the different types of particle size distributions (mass, number, and surface) are available for the same analysis of the sampler. Furthermore, the elemental composition can also be retrieved.

The UNC sampler is so small that using it for indoor stationary sampling is easy. Especially since the UNC sampler can be used indoors and outdoors to study the difference in which particles travel from the outside to the inside. Thus, the particles can be earmarked by size, shape, and elemental composition to know which of the particles are indoor particles and which come from the outside. The need to improve risk assessment from personal exposure to aerosols indoors has just recently started (Morawska et al., 2013).

The health effects of PM$_{10-2.5}$ have not been investigated as extensively as PM$_{2.5}$ and PM$_{10}$, but studies indicate that PM$_{10-2.5}$ needs to be studied as well (Brunekreef and Forsberg, 2005; Adar et al., 2014). There are no legislations for PM$_{10-2.5}$ as there are for PM$_{2.5}$ and PM$_{10}$. Furthermore, calculation of PM$_{10-2.5}$ requires measurements collecting both PM$_{10}$ and PM$_{2.5}$, which can be done in one simple sampling with the UNC sampler, since it encompasses all ranges. Therefore, the UNC sampler could be an alternative to measure PM$_{10-2.5}$ when reporting on PM$_{10-2.5}$. Especially since most UNC sampler studies have focused on method validation for the sampler for PM$_{10-2.5}$ at outdoor sites (Leith et al., 2007; Ott and Peters, 2008a; Ott et al., 2008b,c; Wagner et al., 2012; Wagner and Casuccio, 2014; Peters et al., 2016). The UNC sampler could also be useful for greater coverage in ambient air studies, covering PM$_{2.5}$, PM$_{10-2.5}$, or PM$_{10}$, in parallel with active samplers.

### 5.5 What is next for the UNC sampler?

The purpose of this thesis was to develop more knowledge about the UNC sampler and the possibility of using it for personal sampling of occupational dust exposure. Thus, now we can continue on the path of determining how to use the UNC sampler as a personal sampler. Before the UNC sampler can be used as a personal sampler there are a few things that need to be investigated. The UNC sampler should be studied for personal sampling at several different positions in the breathing zone on a person, to investigate if location on the body makes a difference for sampling. While studying the location on the body, grounding of the sampler should also be made using samplers that are grounded and samplers that are not, in order to study if there is any difference in the amount of particles deposited and where on the collection surface they deposit.

Higher concentration levels that are closer to OELs should be investigated with
the UNC sampler. In our stationary sampling studies we observed that the UNC sampler could differentiate between different concentrations, but our highest concentrations were below 0.8 mg m\(^{-3}\) for respirable fraction, with the OEL for inorganic dust at 5 mg m\(^{-3}\) for the respirable fraction.

The only criterion for respirable fraction is to follow ISO 7708:1995 and EN 481:1993, which is rather easy with the UNC sampler because the concentration of the UNC sampler is only adjusted to the respirable convention. The fact that there is no strict criterion or legislation for respirable fraction as it is when measuring PM\(_{2.5}\) and PM\(_{10}\) enables an easier transition from the respirable cyclone to a passive sampler. Furthermore, for research related to health effects, the UNC sampler also addresses particle size distribution and other characteristics, not only concentration. The respirable cyclone has been used since the 1970s, and unfortunately the field of occupational hygiene has not moved on to new methods. In my opinion we are ready for change and to advance, as is the standard way in occupational hygiene, to develop instruments and procedures when more knowledge is gained and vice versa.
Chapter 6

Conclusions

The main conclusions are:

- The new analysis model for the UNC sampler enables stationary passive sampling of dust exposure with mineral characterisation.

- Changing the analysis model of the UNC sampler, for both stationary and personal sampling measurements, yielded reasonable particle size distributions compared with the distributions from the aerodynamic particle sizer.

- Quicker microscopic image analysis by reducing the number of images for mass concentration calculations to ten results in a negligible loss in precision.

- The UNC sampler is not yet ready for personal sampling. Personal sampling with the UNC sampler showed particles of mineral origin with reasonable particle size distribution, but with approximately 30 times higher particle mass concentrations compared to the respirable cyclone.
Chapter 7

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CHAPTER 7. ACKNOWLEDGEMENTS

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Chapter 8

References


Elgstrand K, Vingård E, editors. (2013) *Occupational Safety and Health in Mining: Anthology on the situation in 16 mining countries.* Occupational and Environmental Medicine, University of Gothenburg.

CHAPTER 8. REFERENCES


CHAPTER 8. REFERENCES


Torén K, Bergdahl IA, Nilsson T, et al. (2007) Occupational Exposure to Particulate Air Pollution and Mortality Due to Ischaemic Heart Disease and


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