

**DETERMINATION OF THE OCCURRENCE OF TOXIC TRACE METALS
AT TWO SITES IN THE NORTH WEST PROVINCE USING SIZE OF
ATMOSPHERIC AEROSOLS**

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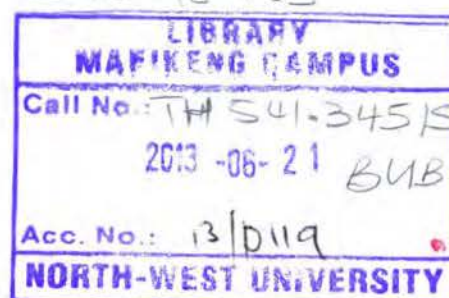


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Declaration

I, Amanda Bubu (Student No: 16575458) declare that the Dissertation titled: "Determination of the occurrence of toxic trace metals at two sites in the North West Province by size of atmospheric aerosols" is the result of my own investigation and research and has not been submitted for any other degree or to any university.

Dedication

This work is dedicated to my mother Miss Boniwe Bubu and my son Kamvalethu Unamandla Bubu for their love, support and guidance.

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ABSTRACT

The concentration levels of atmospheric aerosols of different sizes of particulate matter namely PM₁₀, PM_{2.5}, PM₁ and PM_{<1} were determined in the North West province mining towns of Rustenburg which is a platinum mining town, and Klerksdorp which is a gold mining town. In addition, the presence of the toxic metals lead, chromium, vanadium and nickel in the different particle sizes were determined. At the Rustenburg study site, aerosol data was collected at three hourly intervals on weekdays and weekends during the day. At night time, the data was collected over a period of twelve hours from 18h00 to 06h00 the following morning. At the Klerksdorp site the average sampling time was three hours from 09h00 to 15h00. In addition to aerosol data, meteorological data was also collected continuously and recorded at 3 hourly intervals at the two sites.

The determination of the particle size concentration was made using a three stage Dekati PM₁₀ cascade impactor connected to a pump system which was set to give a flow rate of 30 L/min. The aerosols were collected onto polycarbonate foil filters which had been greased with an Apiezon-toulene mixture and weighed on a Sartorius Analytic A 2005 electronic balance. The chemical analysis of the samples to determine the presence of the toxic elements was done with an FEI Quanta 200 FEG scanning electron microscope.

The PM concentrations were found to be higher at the Rustenburg study site than at the Klerksdorp site. The daytime PM levels went as high as 90 µg/m³ at the Rustenburg site, while at the Klerksdorp site they went as high as 55 µg/m³. The night-time concentrations ranged between 0.04 µg/m³ and 0.8 µg/m³ for Rustenburg, and were from 0.01 to 0.2 µg/m³ for Klerksdorp. The emissions in both areas were ascribed to be mainly anthropogenic in origin.

The elements Cr, Ni, V and Pb were identified in almost all PM samples from the Rustenburg study site. However, only a few samples in the Klerksdorp area contained these toxic elements. The elements also occurred in higher concentrations in Rustenburg

than in Klerksdorp. The higher concentrations for these elements in Rustenburg relates to the type of mining activity. The Rustenburg mines include some that are open-pit unlike those in Klerksdorp which feature underground mining.

Comparison of concentrations with international standards was made. The results obtained on one weekday showed that Cr exceeded the limits of $1 \mu\text{g.m}^{-3}$ for NOISH and also the limit of $1.5 \mu\text{g.m}^{-3}$ for APCEL. Pb did not exceed the WHO standards of $0.5 \mu\text{g.m}^{-3}$, neither did V exceed the levels of $1 \mu\text{g.m}^{-3}$ set by WHO on that same day. The results obtained on another day also showed that Cr exceeded the limits of $1 \mu\text{g.m}^{-3}$ for NOISH but did not exceed $1.5 \mu\text{g.m}^{-3}$ for APCEL. Pb did not exceeded the WHO standard of $0.5 \mu\text{g.m}^{-3}$ nevertheless lead concentrations generally were very high at $0.3 \mu\text{g.m}^{-3}$. The study indicates the need for more prolonged, continuous studies so as to establish trends and seasonal variations in particulate matter and toxic metals.

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LIST OF ABBREVIATIONS AND ACROYNYS

PM	: Particulate Matter
IPM	: Inhalable Particulate Mass criteria
SFU	: Stacking Filter Unit
VOC	: Volatiles Organic Compound
WHO	: World Health Organization
EPA	: Environmental Protection Agency
CCN	: Cloud Condensation Nuclei
IARC	: International Agency for Research on Cancer
PIXE	: Particle Induced X-ray Emission
PIGE	: Particle Induced Gamma-ray Emission
PESA	: Proton Elastic Scattering Analysis
SEM	: Scanning Electron Microscope
EDS	: Energy Dispersive Spectroscopy
EDX	: Energy Dispersive X-ray Detector
APCEL	– Asia Pacific Centre for Environmental Law
NOISH	: National Institute for Occupational Safety and Health
WD	: Working Distance
CL	: Cathodo-Luminescence
Cr	: Chromium
Ni	: Nickel
V	: Vanadium
Cd	: Cadmium
Pb	: Lead

CHAPTER 1

INTRODUCTION

1.1 GENERAL OVERVIEW

Atmospheric aerosols are two-component systems (a gas or gas mixture, most commonly air; and the particles suspended in it) having special properties that depend on the size of the particles, their chemical composition, and their concentration in the suspending medium. Each aerosol species is formed in the atmosphere separately by different processes and the species are mixed together to form particles of mixed composition. Aerosols, in general, consist of sulphates, nitrates, sea-salt, mineral dust, organics and carbonaceous components. It has been said that aerosols have been in the atmosphere since the beginning of time itself. (Sateesh, 1998).

1.1.2 Sources of Atmospheric Aerosol

Atmospheric aerosol particles have a wide variety of natural and anthropogenic sources. They are either emitted as liquids or solids directly into the atmosphere in which case they are referred to as primary particles, or they are formed by gas-to-particle conversion in the atmosphere by nucleation and condensation of gaseous precursors in which case they are referred to as secondary particles. Examples of natural sources of primary aerosols include: the shattering of sea spray into tiny droplets that evaporate before gravitating back towards the water surface, the particles caused by forest fires, the wind driven soil dust, pollen, and volcanic eruptions. Anthropogenic sources of primary particles include vehicular emissions, industrial emissions, combustion of fossil fuels and traffic-related suspension of road dust and construction activities. Although natural aerosols can be as much as 4 times larger than man-made emission on a global scale, there can also be large regional variations of man-made emissions depending on local conditions.

Atmospheric aerosol particles sizes span four orders of magnitude in diameter, from a few nanometre to tens of micrometre. Particles in the air have a variety of shapes for which a geometrical diameter cannot be defined so that an equivalent diameter that depends on a physical property rather than a geometrical one is defined. The diameter of an aerosol is defined as the diameter of a sphere of unit density that would have the same value of a particular physical property as the irregularly shaped particle. Particles in the air can change their size and composition either by condensation of vapour species or evaporation, or by coagulating with other particles whereby two particles collide to form one larger particle, or by chemical reaction or by activation in the presence of water supersaturation to form cloud droplets. Cloud droplets and raindrops can grow even larger and are usually treated separately. Particles are eventually removed from the atmosphere by deposition at the earth's surface (dry deposition) or by precipitation (wet deposition) (Hoppel *et al.* 1990).

Particle size distributions play an important role in the studies of atmospheric aerosols, for example in the apportionment of sources, effect on climate and on human health. The fine particles contain aerosols such as sulphates, nitrates, combustion particles and re-condensed organic and metal vapours. Toxic heavy metal particles have also been found in fine particles (Walter, 2001).

1.2 RESEARCH PROBLEM

Health effects of aerosol particles have raised great interest in the investigation of aerosol properties. The World Health Organization WHO, (2006) has identified atmospheric particulate pollution as one of the most important contributors to ill-health (World Resource Institute, 1999). Numerous studies suggest that health effects can occur at particulate levels that are at or below the levels permitted under national and international air quality standards. According to WHO, (2006), particulate pollution does induce adverse health effects, especially for the more susceptible populations. It has been suggested that the extremely small size of the fine particulate matter (PM) promotes efficient entry and

adherence to the lungs and the toxicity of the particles is mainly responsible for inflicting damage to the organ (Lee, 2002).

Mining activities benefit communities by supplying jobs and creating resources that drive a country's economy. However, many of these communities also have to deal with the resulting pollution that emanates from the mines. In the North West Province, Rustenburg and Klerksdorp are towns where major mining activities take place. The mines in Rustenburg supply most of the platinum produced in South Africa, while Klerksdorp is a major gold mining town.

Airborne emissions occur during each stage of the mine cycle, from exploration to, development, construction, and operational activities. During mining operations large quantities of materials are moved. In addition, mining creates large piles of waste which can contain small size particles that are easily dispersed by the wind. All activities during ore extraction, processing, handling, and transport depend on equipment, generators, processes, and materials that generate hazardous air pollutants such as particulate matter, heavy metals, carbon monoxide, sulfur dioxide, and nitrogen oxide.

The platinum mining industry experienced a boom in the last decades of the last century and the early years of the 21st century. This growth leads to the mining companies operating in the Rustenburg area expanding their activities and increasing production. However, little attention was given to improving the air pollution technology used in the smelters to reduce the amount of air pollution emitted. Consequently due to the potential health hazards resulting from the mining activities in the province, it is necessary to study the atmospheric aerosols around the mining areas. It is important to assess whether the levels of emissions are within local and international standards, and to assess the occurrence of toxic heavy metals that usually accompany mining operations. The areas of Rustenburg and Klerksdorp in the North West Province have been selected for this study mainly due to their potential as sources of large anthropogenic aerosol emissions due to their mining and smelting activities (Lee, 2002).

1.3 OBJECTIVE

The most important aerosol property for this study is the particle size, which, to a great extent determines the behaviour of aerosols since aerosols cover a wide range of particle sizes. Aerosol particle size distributions play an important role in understanding both the detailed aerosol processes, the long-term changes in the atmosphere, and their impact on health. Size distribution functions describe how the aerosol number (or area or volume) is distributed with respect to size. The size distribution mainly depends on the production mechanism or source (Sateesh, 1998).

The objective of this study is thus to determine the occurrence of the toxic metals: Chromium, Lead, Nickel and Vanadium in atmospheric aerosols of different sizes in the Rustenburg and Klerksdorp mining areas of the North West Province. The specific objectives are:

1. to determine the concentration levels of different sizes, where as units for PM are $\mu\text{g.m}^{-3}$ (PM₁₀, PM_{2.5}, PM₁ and PM <1) of particulate matter (PM₁₀ refers to those particles with aerodynamic diameter less than 10 micrometers, and similarly for PM_{2.5}, and PM₁).
2. to determine the presence of the toxic metals Chromium, Lead, Nickel and Vanadium present in different sizes of particulate matter.

The results obtained will benefit the local municipalities in assessing the need for stringent ambient standards. They will provide information to district municipalities when making decisions for implementing the licensing processes in industries with smelters. They will add to the database for the department of health which has regulatory oversight on health issues in the Province

CHAPTER 2

REVIEW OF THE LITERATURE

2.1 SOURCES OF ATMOSPHERIC AEROSOLS

Atmospheric aerosols are emitted into the atmosphere by natural as well as man-made processes. The most important sources of atmospheric particles are direct natural emissions. Globally, the two main mechanisms, accounting for 80 - 90% of the total size distribution particulate mass are waves breaking or bubbles bursting over the oceans (Seinfeld and Pandis, 1998). These release particles consisting mainly of sodium chloride, and windblown mineral dust from deserts and other arid areas.

Many of the pollutants of concern are formed and emitted through natural processes. Examples of naturally occurring particulates include pollen grain; fungus spores, salt spray, particles from forest fires, and dust from volcanic eruptions. Gaseous pollutants from natural sources include carbon monoxide as a breakdown product in the degradation of hydrogen sulfide resulting from the breakdown of cysteine and other sulfur containing amino acids by bacterial action, methane and oxides of nitrogen. Man-made sources of pollutants can be conveniently classified into stationary combination, transportation, industrial process and solid waste disposal sources (Seinfeld and Pandis, 1998).

On spatially or temporally limited scales biogenic emissions such as leaf wax, viruses, pollen and volcanic emissions of sulphate particles can contribute significantly to atmospheric particle mass. On the other hand, anthropogenic sources like biomass, fossil fuel burning which releases mainly soot and organic particles can emit high local concentrations of inhalable particles and hence cause considerable public health effects. In addition, human activities have reduced vegetation, disturbed soil surfaces and thus enhanced mineral aerosol production (Clarke *et al.* 1999).

The different types of particle sources for atmospheric aerosols are dust, volatile organic compounds (VOC's), sulfur dioxide and ozone. Aerosols are responsible for reduced visibility in the atmosphere, and the coefficient of haze is a measurement of the amount of dust and smoke in the atmosphere. Sources of dust and smoke include motor vehicle emissions, industrial emissions, road dust, wind blown soil, dust resulting from human activities such as agriculture operations, smoke from forest fires and smoke from recreational sources (i.e. camp fires and fireplaces).

VOC's include a large group of chemicals containing carbon and hydrogen atoms that can react quickly to form other chemicals in atmosphere. VOC's are important because they can react with oxides of nitrogen in the presence of sunlight to form ozone and photochemical smog and are also toxic to humans, animals or vegetation. The major sources of VOC's are vegetation, automobile emissions, gasoline marketing storage tanks, petroleum, chemical industries, dry cleaning, fireplaces, natural gas combustion and aircrafts. VOC's emissions from natural sources, such as forests, grasslands and swamps are estimated to be almost six times greater than human sources. Individual VOC's are also produced from leaking valves, flanges, pumps and compressors at industrial facilities (Seinfeld and Pandis, 1998).

Coal, oil and other fossil fuels contain sulfur. When these fuels burn, sulfur dioxide is formed. Sulfur dioxide is also emitted from power plants, oil refineries, foundries and steel mills. Natural sources such as volcanoes also emit sulphur dioxide. Sulfur dioxide has a bad odour and can irritate the respiratory system. It can constrict the bronchi and increase mucus flow making breathing difficult, irritate the lungs and throat, increase respiratory illness, enhance the harmful effects of ozone, damage plants and reduce visibility (Clark *et al.* 1999).

Ground level ozone is the major component of the photochemical smog that blankets many urban areas. It is not emitted directly but is formed when nitrogen oxides from fuel combustion react with volatile organic compounds such as unburned gasoline or paint solvents in the atmosphere. Sunlight and heat stimulate ozone formation causing peak

ozone levels generally to occur in summer. As a powerful oxidant, ozone can react with nearly any biological tissue (Seinfeld and Pandis, 1998).

Emissions are released into the atmosphere by natural processes as well as by human processes and activities. Common anthropogenic sources of atmospheric emissions in South Africa include the following:

1. Industrial and commercial activities and the operations of smaller emitters such as dry-cleaners as well as non-domestic fuel-burning equipment used by businesses, hospitals, and schools.
2. Electricity generation, specifically coal-fired and oil-fired power stations generating electricity for the national grid.
3. Waste treatment and disposal including waste incineration, landfills, and wastewater treatment works.
4. Residential activities, specifically household combustion of coal, paraffin, liquid petroleum (LP) gas, dung and wood.
5. Transport, including petrol- and diesel-driven vehicle exhaust emissions; road-dust raised by vehicles; brake- and tyre-wear fugitives and rail-, shipping-, and aviation-related emissions.
6. Mining, comprising fugitive dust releases and emissions from spontaneous combustion.
7. Agriculture, including emissions from burning crop residue, enteric fermentation, and the application of fertilizers and pesticides.
8. Informal/miscellaneous, including tyre burning and fugitive dust from construction activities and the erosion of open areas (State of air report in South Africa, 2005).

2.2 CLIMATE EFFECTS OF AEROSOLS

Aerosols can, depending of their concentration, size and chemical composition, absorb and scatter incoming and outgoing radiation and in this way affect the earth's radiation balance and consequently the earth's climate. These primary parameters that determine

the effects of aerosols on the environment and on climate however, vary with time and from one place to another.

Particles can affect the climate in two different ways. The "direct effect" is caused by the fact that the particles scatter and absorb solar and infrared radiation in the atmosphere. The earth's climate depends on the amount of solar radiation that is either absorbed or reflected by the earth. Different types of aerosols react differently when they interact with sunlight, for instance sea salt particles reflect sunlight back out into space while black carbon particles from burning of wood or fossil fuels absorb most of the sunlight that interacts with them.

The "indirect effects" of particles are more complex and more difficult to assess but they include the fact that aerosols act as condensation nuclei for the formation of clouds. The addition of particulate matter into the atmosphere causes the water in the atmosphere to condense onto the particles. The smaller droplets in the clouds that changes in the concentration of aerosols in the atmosphere cause variations in the density and size of cloud droplets. Both direct and indirect radiative forcing are influenced by particle size, composition and relative humidity. Atmospheric aerosols thus affect the climate through the earth's radiation balance both directly by scattering and absorbing incoming solar radiation, and indirectly by acting as cloud condensation nuclei (CCN).

Human activities have also increased the concentrations of aerosols in the atmosphere. The report of the International Panel of Climate Change (IPCC, 1996) reveals that anthropogenic aerosols pose a big threat to the climate. Elevated and uncontrolled amounts of aerosols in the atmosphere tend to change atmospheric gaseous state, thereby affecting rainfall patterns and causing temperature fluctuations. Measurements to determine these effects are done by estimating the value of the mean surface temperature T of the earth from a simple balance of incoming and outgoing radiant energy. By assuming that the earth is a black body so that it absorbs all of the incident solar energy, the rate at which energy is absorbed is $\pi R_e^2 S_0$, where $R_e = 6378$ km is the radius of the earth, and S_0 , the solar constant, is the power per unit area intercepted at the Sun-Earth

distance (1365 to 1372 W.m⁻²). The earth cannot be a perfect black body, for then we would not see the land, ocean, or vegetation by reflected light. The fraction of the light which these objects (land, oceans, etc) reflect is such that to a good approximation the surface of the earth can indeed be considered a black body. The energy balance is then maintained by the rate at which energy is absorbed and the mean rate at which it is radiated;

$$\text{i.e. } \pi R_e^2 S_o = 4\pi R_e^2 \sigma T^4 \quad (1)$$

where σ is the Stefan-Boltzmann constant given by $\sigma = 5.670 \times 10^{-8} \text{W/m}^2 \text{K}^4$. This leads to a mean surface temperature T given by

$$T^4 = S_o / 4\sigma \quad (2)$$

Taking the fourth root of both sides yields $T = 278^\circ \text{K}$ (Sateesh, 1998). This equation does not give a good approximation for the earth's mean temperature. To refine the approximation of the mean temperature of the earth, the fact that the earth is not a blackbody has to be taken into account. The earth reflects a substantial portion of the incident radiation and therefore reduces the amount of radiant energy which reaches the surface. Most of this radiation detected by satellites had originated in the upper atmosphere where the temperature is lower than it is on the surface of the earth. Thus the atmosphere must play a role in compensating for the fraction of solar energy, which is reflected (Sateesh, 1998).

The fraction of incident solar radiation that is reflected by a planet is termed its *albedo* and is denoted by a . For the purpose of calculating a planet's temperature, it is the amount of energy absorbed that is required. The fraction of solar radiation absorbed is $(1-a)$, so that the expression for the energy absorbed is modified to be: $S_o \pi R_e^2 (1 - a)$. Since the energy

radiated by the earth is $4\pi R_e^2 \sigma T^4$, in the steady state, when the amount of solar energy absorbed equals the emitted energy, we have:

$$(4\pi R_e^2) \sigma T^4 = (1 - a) \pi R_e^2 S_o \quad (3)$$

where R_e is the radius of the earth, T_e is the global temperature. The mean solar radiation incident at the top of the atmosphere is $\sim 343 \text{ W.m}^{-2}$ out of which $\sim 103 \text{ W.m}^{-2}$ is reflected back to space by the earth's surface and atmosphere. Thus the value of a is ~ 0.3 . The energy balance equation implies that a change of 0.005 in the value of a results in a 0.7% change in the global temperature (IPCC, 1996).

The atmosphere has a pronounced effect on the energy balance because its constituents selectively absorb radiation within certain wavelength bands. In this way the solar energy spectrum is altered by absorption as the incident radiation penetrates the earth's atmosphere. The ratio of received energy at each wavelength into the atmosphere can result in absorption spectra for the ultraviolet and infrared portions of the electromagnetic spectrum (Seinfeld and Pandis, 1998).

The warming of the earth's surface resulting from the fact that the atmosphere is largely transparent to solar radiation is called the green-house effect. It is this effect which maintains the surface temperature of the earth about 40° K higher than is dictated by simple energy balance consideration of the incoming and outgoing radiation.

A certain fraction of incident energy from the sun is reflected or scattered into space without absorption. For the earth and its atmosphere as a unit, this fraction called albedo has a values estimated to be between 0.30 and 0.39 (Sateesh,1998). From this, about 0.25 is attributed to reflection from clouds and only 0.03 to reflection from the surface of the earth. Thus the albedo of the surface alone is about 0.06, since only half of the

incoming radiation penetrates through the atmosphere and is incident on the surface. The remainder of the albedo is believed to arise from scattering by aerosols and atmospheric gases (Seinfeld and Pandis, 1998).

2.3 HEALTH EFFECTS OF AEROSOLS

The causal linking of the occurrence in the atmosphere of particulate matter (PM) with adverse health effects has been recognized for a long time. Many studies have reported that people exposed to high concentrations of PM, particularly fine particles, show increased respiratory symptoms, outbreaks of cancer and even increased mortality rates (Dockery and Pope, 1994; Espinosa *et al.* 2001; Shah *et al.* 2006). There are large numbers of studies of gaseous pollutants and particulate matters (PM10 and PM2.5) which have shown that air pollution can cause harm to humans and their health (Nation Public Health Institute, 2005). The worst affected are those who already have respiratory diseases.

It has been found that asthma epidemic is limited to areas with high PM2.5 particulate pollution, with unpolluted areas having little occurrence of asthma (Nation Public Health Institute, 2005). PM2.5 is therefore harmful to humans. PM2.5 particles generated from vastly increased vehicle traffic emissions comprise contaminated carbon from inadequate quality fuels, platinum from catalysts and tyre particulates. PM2.5 generated from industrial emissions of heavy metals especially nickel, vanadium, cadmium, lead and mercury with acidic carbon are particularly harmful substances. PM2.5 is also produced by open-casting of quartz and coal.

Heavy metals associated with respirable particles have also been shown to increase lung or cardiopulmonary injuries caused by particulate air pollutant exposure (Espinosa *et al.* 2001; Cancio *et al.* 2008; Leili *et al.* 2008). Heavy metals contained in fine particle pollution from the industries can penetrate deeply into the lungs, and cause lung difficulties and

permanent lung damage. Exposure to high levels of fine particulates causes heart disease. The lung inflammation from inhaling particulates or irritants results in enhanced clotting, increasing the likelihood of heart attacks and strokes. PM_{2.5} affects people with acute respiratory infections or defects in the heart electrical control system (Agency for Toxic Substances and Disease Registry, 1993).

Several epidemiological studies from various parts of the world with different data sets and techniques have implicated particulate matter as a serious threat to human health. From those studies statistical association has been found between adverse health effects and PM₁₀. Studies recently conducted with PM_{2.5} have shown an even stronger association between health outcomes and particle size range. These findings have led researchers to make further studies on the association between smaller particles of air pollutants and causes of respiratory diseases. Several studies are increasingly focusing on the role of the particle size composition in particulate matter and health problems (Agency for Toxic Substances and Disease Registry, 1993).

The state of the air is of utmost importance to the health of human beings and living things at large. It is a known fact that particulate matter plays a big role in our physiology. Breathing particulate matter of size ten micrometres (PM₁₀) or less can affect the respiratory system amongst other health problems. It has been reported from previous studies for instance, that esophageal cancer is high among men and women in northern Iran and this was linked to the occurrence of certain trace elements including Ni and Pb (Azin *et al.* 1996).

2.3.1 Health Effects of Toxic Trace Metals

The toxic trace metals discussed herein are chosen because of the nature of mining activities in the Rustenburg and Klerksdorp areas where the research was conducted, and the effects of the metals on human health.

1. Lead

Lead is a toxic heavy metal. Secondary sources include iron and steel production, lead smelting, battery and lead alkyl manufacturing and motor vehicle emission. The introduction of the catalytic converters in cars' exhaust systems has, however, led to a great decrease in lead emissions from cars. The catalytic converters which are required in order to meet emission standards are ruined by leaded gasoline (Agency for Toxic Substances and Disease Registry, 1999).

People, animals and fish are exposed to lead mainly by breathing and ingesting it in food, water, soil and dust. Lead accumulates in the blood, muscles and fat. Infants and young children are especially sensitive to even low levels of lead. Lead causes damage to the kidneys, livers, brain, nerves and other organs. Exposure to lead may also lead to osteoporosis (brittle bone disease) and reproductive disorders. Excessive exposure to lead causes seizures, mental retardation, behavioural disorders, memory problems and mood changes. Low levels of lead that are less than $0.2 \mu\text{g}/\text{m}^3$ can damage the brain and nerves in foetuses and young children. Lead exposure causes high blood pressure and increases incidences of heart disease, especially in men. Lead exposure may also lead to anaemia. Wild and domestic animals can ingest lead while grazing. Low concentrations of lead can slow down vegetation growth near industrial facilities. Lead can enter the water system through runoffs and from the sewage and industrial waste streams. Levels of lead that are more than $1 \mu\text{g}/\text{m}^3$ in water can cause blood and neurological changes in fish and other aquatic animals. Lead also adversely affects reproduction in some aquatic animals. The lead problem has however, decreased in many countries because of the phasing out of lead in gasoline (Agency for Toxic Substances and Disease Registry, 1999).

2. Chromium

Chromium is a naturally occurring element found in rocks, animals, plants, soil and in volcanic dust and gases. It is present in the environment in several different forms. The most common forms are chromium(0), chromium(III), and chromium(VI). No taste or odour is associated with chromium compounds. Chromium(III) occurs generally in the environment and is an essential nutrient. Chromium(VI) and chromium(0) are generally produced by industrial compounds. The metal chromium, which is the chromium(0) form, is used for making steel. Chromium(III) and chromium (VI) are used for chrome plating, dyes and pigments, leather tanning, and wood preservation (Agency for Toxic Substances and Disease Registry, 2000).

Chromium enters the air, water, and soil mostly in the chromium(III) and chromium(VI) forms. In air, chromium compounds are present mostly as fine dust particles, which eventually settle over land and water. Chromium can strongly attach to soil and only a small amount can dissolve in water and move deeper into the soil to underground water (Resane, 2004).

Humans can be exposed to chromium(VI) through eating food containing chromium (III) and drinking contaminated water. Breathing high levels of chromium(VI) can cause ulcers and holes in the nasal septum. Ingesting large amounts of chromium(VI) can cause stomach upsets and ulcers, convulsions, kidney and liver damage, and even death (Nation Public Health Institute, 2005).

Skin contact with certain chromium(VI) compounds can cause skin ulcers. Allergic reactions consisting of severe redness and swelling of the skin have been noted. The Environmental Protection Agency (EPA) has determined that chromium(VI) in air is a human carcinogen (Nation Public Health Institute, 2005).

3. Nickel

Pure nickel is a hard, silvery-white metal that can combine with other elements such as chlorine, sulfur, and oxygen to form nickel compounds. Many nickel compounds dissolve fairly easy in water and have a green colour. Nickel compounds are used for nickel-plating, colouring ceramics, making batteries and as catalysts (Agency for Toxic Substances and Disease Registry, 1993).

Nickel is released into the atmosphere by industries that make or use nickel, nickel alloys, or nickel compounds. It is also released into the atmosphere by oil-burning power plants, coal-burning power plants, and trash incinerators (Agency for Toxic Substances and Disease Registry, 1993). Nickel released in industrial wastewater ends up in soil or sediment where it strongly attaches to particles containing iron or manganese (Agency for Toxic Substances and Disease Registry, 1998).

In air, it attaches to small particles of dust that settle to the ground or are taken out of the air in rain or snow. This usually takes many days. Nickel in PM_{2.5} particulates in the lungs enters the bloodstream and excites the heart's electrical system leading to tachycardia, while lead and iron particulates harm heart muscles. The most common harmful health effect of nickel in humans is an allergic reaction. People can become sensitive to nickel when jewellery or things containing it are in direct contact with the skin for a long time. Once a person is sensitised to nickel, further contact with the metal may produce a reaction (Agency for Toxic Substances and Disease Registry, 1993).

Nasal sinus has resulted when workers breathe dust containing high levels of nickel compounds while working in nickel refineries or nickel processing plants. The International Agency for Research on Cancer (IARC) has determined that some nickel compounds are carcinogenic to humans and that metallic nickel may also possibly be carcinogenic to humans. The Environmental Protection Agency (EPA, 1997) has also determined that

nickel refinery dust and nickel sub-sulphides are human carcinogens. Damage to the lung and nasal cavity has been observed in rats and mice inhaling nickel compounds. Eating or drinking large amounts of nickel has caused lung disease in dogs and rats and has affected the stomach, blood, livers, kidneys, and immune system in rats and mice, as well as their reproduction and development (Agency for Toxic Substances and Disease Registry , 1993).

4. Vanadium

Vanadium is an element that occurs in nature as a white-to-gray metal, and is often found as crystals. Pure vanadium has no smell. It usually combines with other elements such as oxygen, sodium, sulphur or chloride. Vanadium and vanadium compounds can be found in the earth's crust and in rocks, some iron ores, and crude petroleum deposits (Agency for Toxic Substances and Disease Registry, 1993).

Vanadium is mostly combined with other metals to make special metal alloys. Vanadium oxide is a yellow-orange powder, dark-grey flakes, or yellow crystals. Some amounts of vanadium are used in making rubber, plastics, ceramics, and other chemicals; it is also mixed with iron to make important parts for aircrafts engines (Agency for Toxic Substances and Disease Registry, 1993).

Vanadium mainly enters the environment from natural sources and from the burning of fuel oils. It can stay in the air, water, and soil for a long time. Low levels have been found in plants, but it is not likely to build up in the tissues of animals (Agency for Toxic Substances and Disease Registry, 1993).

Exposure to high levels of vanadium can cause harmful health effects. The major effects from breathing high levels of vanadium are on the lungs, throat, and eyes. Workers who

inhale it in for short and long periods sometimes develop lung irritation, coughing, wheezing, chest pain, running nose, and a sore throat. These effects start soon after inhaling the contaminated air. Similar effects have been observed in animal studies (Agency for Toxic Substances and Disease Registry, 1993).

It has been observed that people living in industrial areas have relatively higher concentration of metals like Pb and Cadmium (Cd) in their blood. Due to their toxicity to ecosystems in general and humans in particular heavy metals have been studied as a class of environmental pollutants requiring particular attention. It is essential that their concentration in the atmosphere be reduced substantially in different environmental compartments.

2.4 OTHER STUDIES OF AEROSOL SIZE DISTRIBUTIONS

Many studies have measured size distribution using cascade impactors and elemental composition using PIXE analysis. In Europe, data for this type of work was collected during three epidemiological studies conducted during 1995-1999 in Finland (Number of measurements days N = 36; Helsinki 1996-1997, N = 185 and 1998-1999, N = 182), the Netherlands (Amsterdam 1998-1999, N = 237) and in Germany (Erfurt 1998-1999, N = 177). The mass and number concentrations of several size distributions of particulate matter were monitored on a daily basis during winter and spring months (Nation Public Health Institute, 2005).

In another study carried out in Europe aerosols deposits on filters from ten Romanian towns with different kinds and levels of industrial development were analyzed by PIXE method and the ratios of trace elements to calcium calculated (AncaBancuta *et al.* 2006).

In England measurements were conducted at a rural and an urban site near Colchester to determine the metal content of coarse atmospheric aerosol and the samples were analyzed by PIXE. The results indicated that the trace metals (Mn, V, Cu, Cr) constituted

a more significant part of the coarse mass at the urban site than at the rural site (Eleftheriadis and Colbeck, 2001).

The size distribution using cascade impactors and analysis using PIXE research has also been conducted in Africa (the Republic of Congo, Zimbabwe and South Africa), the Brazilian Amazon region, northern Australia and Indonesia. The emphasis in the studies was placed on the impact of biomass burning and natural biogenic emissions on the climatically active fine aerosols. In Congo samples were collected during the dry season, and were analysed for up to 26 elements by PIXE (Roberts, 2001).

There are researchers who participated in the ground component, and especially in the component at Balbina (1°55'S, 59°24'W, 130km North of Manaus) in Brazil. At this site aerosol samples were taken in 1998 with various types of filter samplers and cascade impactors. The bulk analyses on the filter samples included measurements of PM of up to 50 elements. The cascade impactor samples, in contrast, were only analysed for elements (by PIXE) (Roberts, 2001).

It is to be noted that many studies were based on only a few accelerators, that is, the same research groups were involved in them. This has been possible because there are local PIXE groups interested in aerosol analysis. As a result, these cities offer better chances for receptor model investigations. The research groups have used other complementary techniques, and some tried to compare the results obtained with PIXE and other methods. This obviously makes the results more comprehensive (Mirenda, 1994).

The results of the studies of aerosols in large urban areas based on PIXE are as diverse as the cities themselves. The geographical and climatic characteristics, together with the traffic density and industrialisation of the region, affect the composition of the aerosols. In certain works, the sulphur concentrations (sulfate or coal burning) are in most cases between 3 and 5 $\mu\text{g}/\text{m}^3$, although extreme cases have been observed in Milan (of the order of 10 $\mu\text{g}/\text{m}^3$), and in St. Petersburg (below 1 $\mu\text{g}/\text{m}^3$). Vanadium, as a tracer of fuel

oil, in many cases lies below the minimum detectable limits. On the other hand, Fe, normally associated with soil dust, may be highly influenced by the geographical characteristics of a zone. Thus, Mexico City, situated on a normally dry region, has relatively high Fe concentrations, which may also be enhanced by traffic-related dust. Beijing data is said to have been affected by an episodic industrial emission (Winchester and Bi, 1984) thus explaining the very high figures for Fe. Therefore, Mexico City, which showed extreme concentrations (Miranda, 1994), must have an industrial composition (because the sampling site was in the middle of an important industrial zone), while in Beijing it was attributed to refuse incineration (Yin *et.al.* 1992). Finally, Pb is the characteristic element of traffic-related aerosols. It is also seen that Pb contents are not related to the number of inhabitants in the city, but it should rather be influenced by the quality of the gasoline consumed in that area (Yin *et.al.* 1992).

The collected samples have been analysed using different analytical techniques (nuclear-related techniques and chemical analysis) to characterise the atmospheric aerosol. A comparison among the results obtained by PIXE, Particle Induced Gamma-ray Emission (PIGE) and Ion Chromatography (IC) analysis of samples collected in Serra do Navio (0° 54' N, 52° 0' W), in the northeast part of the Amazon Basin has been made. The precision of PIXE method is around 20%, and the detection limit for black carbon for sample volumes and filter areas used is about 50 $\mu\text{g}/\text{m}^3$. PIXE was used in Brazil to measure concentrations of up to 28 elements (Mg, Al, Si, P, S, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Au, Hg, Pb). The samples were irradiated by a 2.4 MeV proton beam, supplied by a dedicated NEC (National Electrostatics Corporation) SSDH tandem Pelletron accelerator facility, at the LAMFI (Laboratório de Análise de Materiais por Feixes Iônicos) from University of São Paulo. Detection limits are typically 3 $\mu\text{g}/\text{m}^3$ for elements in the range $13 < Z < 23$ and 0.1 $\mu\text{g}/\text{m}^3$ for elements with $Z > 22$. These detection limits were calculated based on a sampling flow rate of 151 litres per minute, sampling time of 72h and irradiation time of 600s. The precision of the elemental concentration measurements is typically less than 10 with 20% for elements with concentration near the detection limit (Miranda, 1994).

CHAPTER 3

METHODOLOGY

This chapter summarizes the methods used in carrying out this study. It describes the principle of operation of the cascade impactors used in the sampling of particles, and those of Particle Induced X-ray Emission (PIXE) which was used to analyse the filters.

3.1 CASCADE IMPACTORS

Cascade impactors measure the size distribution and respirable mass fraction of airborne particle in outdoor and indoor environments. The Dekati PM10 cascade impactor is said to be the finest device that is commercially available (Maeuhaut *et al.* 2002). An important advantage of the cascade impactor is that it operates at a nominal flow rate of $40 \mu\text{g}/\text{m}^3$ which meets the specifications of the U.S. EPA (EPA, 1997).

Impaction stages have a sharp cut-off (D50%) at nominal values of 10, 2.5 and 1 microns. The small 25 mm diameter collection foils and 47 mm absolute back filter are ideally suited for subsequent chemical analysis. The Dekati PM10 impactor is frequently used in combustion applications such as stack measurements as well as ambient air measurements (Hinds, 1999).

The filters used in the impactor for collection of ambient air give the opportunity to analyse (e.g. chemical or gravimetric) a number of small size intervals. Some drawbacks are the risk of bounce off from one stage to the next (i.e. particles of wrong size at some of the stages), as well as the problem of obtaining sharp cut-off diameters in the last stages (cut-off diameter less than $0.1 - 0.2 \mu\text{m}$). Coating the impaction plates with oil or some other sticky substance, which traps the particles more effectively, can reduce the risk of bounce off (Hinds, 1998).

The Dekati PM10 impactor classifies airborne particles into three or four stages for determining aerodynamic particle size distribution. In this study the impactor cut-diameters were selected so that PM10, PM2.5 and PM1 concentrations can be determined simultaneously. The filter stage after the PM1 stage collects all particles smaller than 1 micron. Dekati PM10 impactor operation is based on inertial classification, and gravimetric analysis of the aerosol particle. Particles are collected on 25 mm diameter substrates that are analysed gravimetrically and chemically after the exposure. Dekati PM-10 Impactors are available with flow rates of 10, 20, and 30 l.min⁻¹ (Maeuhaut *et al.*2002). Table 3.1 shows Cascade Impactor Operation Flow.

Table 3.1 : Cascade Impactor Operation Flow

Nominal air flow	10, 20 and 30 l/min
Particle range	0 - 10 µm
Substrate diameter	25 mm
Filter diameter	47 mm
Number of channels	3 or 4 depending on set-up
Operation temperature range	0 - 200 °C
Weight	2,4 kg
Dimensions	ø76 x 180 mm
Impactor material	Stainless steel
Flow control	± 5 % accuracy required for ± 2.8 % accuracy in D50 % values

3.1.1 Operating Principle

The Dekati PM-10 Impactor is a cascade impactor, which collects particles size selectively. The impactor has two co-linear plates one of which has a small nozzle in the centre. The sample of aerosol passes through this nozzle at high speed and makes a sharp turn with the flow between the plates. Particles with sufficient inertia cannot follow the flow and

impact on the second plate; while particles with small enough inertia remain in the flow. Figure 3.1 shows the inside of a cascade impactor.

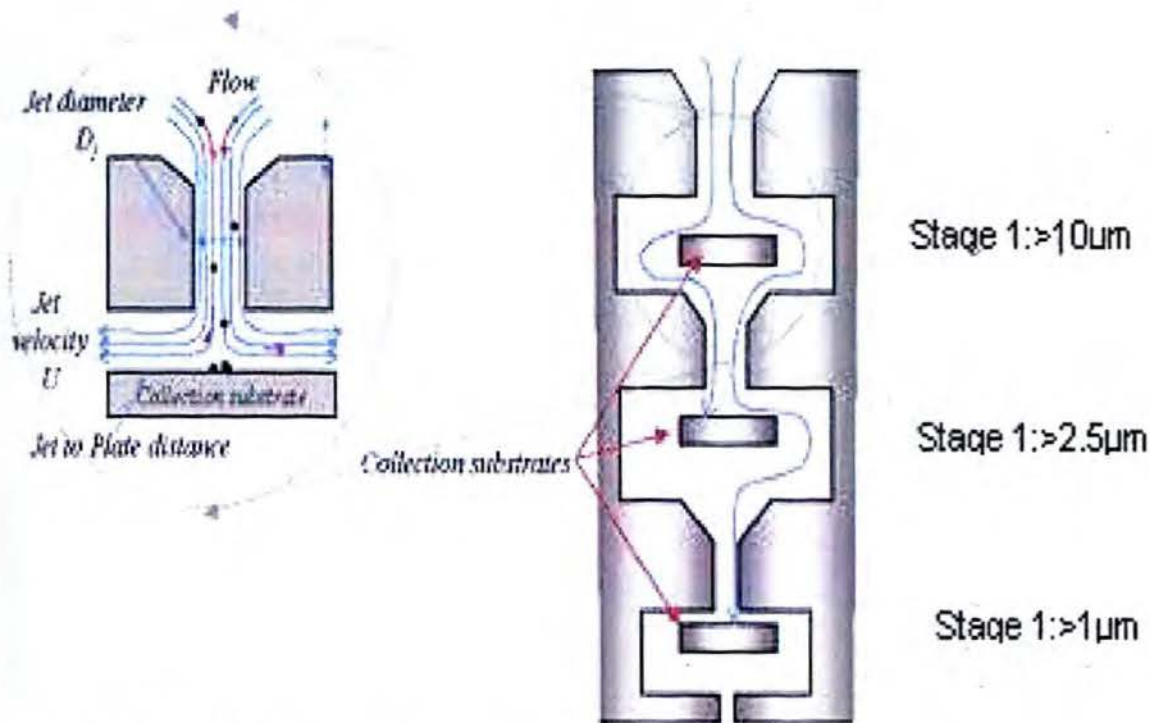


Figure 3.1: PM 10 Dekati Cascade Impactor

The cut diameter for the impactor is defined as the size of particles collected with 50 % efficiency. The plate with a nozzle in it is called the jet plate, and the other plate is called the collection plate. Cascade impactors have several successive impactor stages with decreasing cut diameters (Maeuhautet *al.* 2002).

In a cascade impactor, the particles are sized by their aerodynamic size. Aerodynamic size determines the trajectory of the particle in a gas stream because it accounts for all three major aerodynamic factors: size, shape and mass density. The direct measurement of cascade impactors is defined as the size of a spherical particle that has the same terminal settling velocity as the sampled particle. Aerodynamic size is the most important size in particle work because it determines the penetration of particles in the human lung, the particle collection efficiency in pollution control equipment, and the transport and

diffusion of particles in the ambient air. The Volume flow rate can be measured by a rotameter or by pressure differential measurement before and after the filter stage (Maeuhaut *et al.*2002).

3.2 PARTICLE INDUCED X-RAY EMISSIONS (PIXE)

There is a wide variety of sampling devices available for use in aerosol studies, however, the most common is the stacking filter unit (SFU) which allows particle size separation in two sequential filters: one for particles between 15 and 2.5 μm , and the other for sizes below 2.5 μm . Cascade impactors have also been used to obtain a finer size resolution. The most common filter for aerosol collection by far is the polycarbonate nuclepore. Probably, this popularity is due to its low cost, availability, radiation resistance, and ease of handling. Although not well suited for other analyses, such as proton elastic scattering analysis (PESA) for hydrogen detection, it can be used reliably for PIXE or for X-ray fluorescence (XRF) examinations (Tabacniks *et al.*1993).

Particle Induced X-ray Emissions is a non-destructive technique for rapid analysis of over 40 trace elements with ppm sensitivity. It provides absolute analysis with respect to reference standards and is commonly used to study biological materials and many forms of contamination (Zhang *et al.*2003).

3.2.1 The basic principle of PIXE

X-rays may be produced following the excitation of target atoms induced by an energetic incident ion beam of protons or alpha particles. The incident ions themselves may undergo further elastic or inelastic scattering during the collision. The excited target atom seeks to regain a stable energy state by reverting to its original electron configuration. In doing so, the electronic transition which takes place, may be accompanied by emission of electromagnetic radiation in the form of X-rays characteristic of the excited atom (Zhang *et al.*2003).

Zhang and his colleagues also showed that the emission consists of K, L, and M, lines produced by electron transitions to the K, L, and M shells of the target atom. Hence, elemental composition analysis can be accomplished by determining the X-ray emissions emanating from the excited sample. Either an X-ray photon is emitted or electron emission can take place. Thus the bombardment with ions of sufficient energy (usually MeV protons) produced by an ion accelerator will cause inner shell ionisation of atoms in a specimen. This results in outer shell electrons dropping down to replace inner shell vacancies. X-rays of a characteristic energy of the element are emitted. However only certain transitions are allowed and an energy dispersive detector is used to record and measure these x-rays and the intensities are then converted to elemental concentrations.

PIXE analysis consists of two parts. The first is to identify the atomic species in the target from the energies of the characteristic peaks in the X-ray emission spectrum and the second part is to determine the amount of a particular element present in the target from the intensity of its characteristic X-ray emission spectrum. This normally requires knowledge of the ionization cross-sections, fluorescence yields and absorption coefficients (Zhang *et al.* 2003).

3.2.2 Basic Advantages of PIXE

1. High Sensitivity

Compared to electron based X-ray analytical techniques such as energy dispersive spectroscopy (EDS), PIXE offers better peak to noise ratios and consequently much higher trace element sensitivities. Absolute trace sensitivity to a given trace element is dependent upon a number of factors, such as matrix composition, detector efficiency and peak overlap. However, tests performed on the Harvard system have produced parts per million (ppm) level measurements for certain elements (Zhang *et al.* 2003).

2. Multi-element Capability

Elemental analysis is performed for any element from sodium to uranium in a single spectrum on the system. X-rays from elements below sodium cannot be seen because they are absorbed in either the detector window, the atmosphere between the sample and the detector, or through any filters used. For trace element analysis, a filter has to be chosen to attenuate the X-rays at the energies of the major elements allowing the detector to measure the trace elements with greater sensitivity. Although these filters usually cause insensitivity to lighter elements, they will allow analysis of any element above the filter's absorption edge (Zhang *et al.*2003).

3. The Ideal Specimen

The ideal specimen should be flat and of uniform composition. Since most of the characteristic X-rays emanate from the top few microns, for accurate measurements it is important that the sample be homogeneous within the micron level. A precious object may have a hidden layered structure, or not have a flat or even surface. An X-ray is advisable to analyze a number of spots and take the average. Such measurements are considered to be qualitative or at best "semi-quantitative"(Zhang *et al.*2003).

4. The Benefit of X-ray Filters

At very high count rates, Si(Li) X-ray detectors will behave in a less than ideal fashion. Energy resolution could become significantly worse causing peaks to overlap. Pileup peaks may appear which manifest themselves as multiples of principal peaks. X-ray peaks from major elements can occupy much of the detectors useful counting capability. Dominant low energy X-rays may be filtered out so that the detector will only see contributions due to the higher energy trace or minor elements. Beam current may now be increased with an overall effect of much greater trace element sensitivity while keeping the detector at a low count rate.

In some cases single element foils may be used as "notch" filters to attenuate only a dominant matrix element but allow relatively high transmission of all other X-rays. A good rule of thumb in this case is that the best absorbing filter is lighter than the dominant matrix element by 2 atomic numbers, so that for instance the best filter for a Fe matrix would be a Cr foil (Zhang *et al.* 2003).

3.2.3 Particle (Electron) induced X-ray emission

All particle beam instruments, while quite different in design, offer overlapping capabilities. Whereas scanning electron microscopes (SEMs) have been historically used as cameras and micro-analyzers used for elemental analysis, modern electron probes offer both capabilities while optimizing for one or the other. For example, PIXE (SEM) can quantify X-rays with its energy dispersive X-ray detector (EDX), but it is designed for ease of use and for a variety of specimens (Chong *et al.* 2002).

Electron probe micro-analyzers are designed from the ground up for the analysis of X-rays, which are emitted from the specimen when probed with an electron beam. The design considerations primarily accommodate three to six wave dispersive x-ray spectrometers, which are inherently large. Specimens prepared for X-ray microanalysis are generally flat, and the microprobe analyser is designed to allow only a considerable amount of x and y translation rather than the specimen manipulation which is typical of the SEM (for example, full rotation and tilt). Like a radio that needs to be tuned to your favourite station's wavelength, these spectrometers need to be tuned to the wavelength of the element's characteristic X-ray. That is to say, if the measurement of 9 elements is desired (e.g., Pb, Cr, Al, Fe, Mn, Mg, Ca, Na & K), then the tasks of counting their characteristic X-rays can be distributed across several spectrometers, with extended counting times for minor and trace elements thus, the requirement for more than one spectrometer (Roberts , 2001).

The usefulness of quantifying elemental compositions is invaluable in the sciences of mineralogy, petrology and materials research. Here the researcher is interested in not only

the absolute elemental concentration, but also the spatial distribution of elemental concentrations. New software and hardware will allow elements to be qualitatively or quantitatively mapped, over almost any area on a sample (Roberts, 2001).

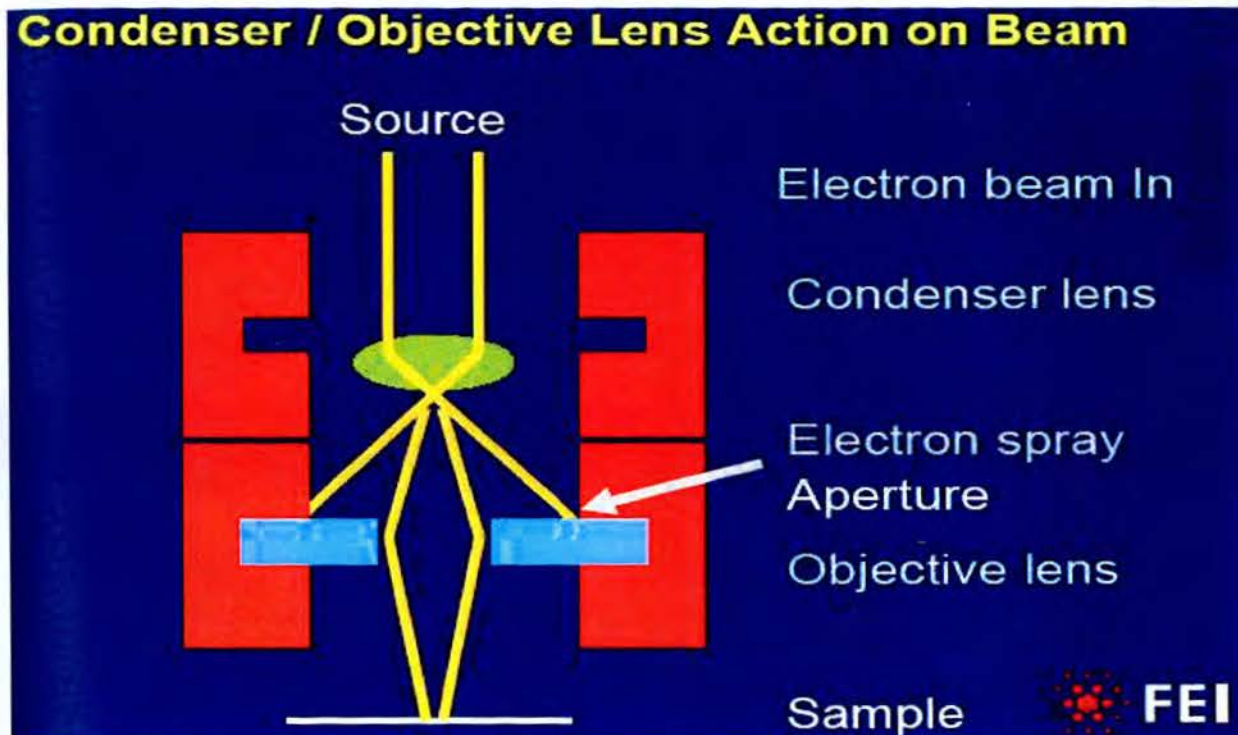


Figure 3.2: FEI Quanta 200 FEG Scanning Electron Microscope (SEM)

FEI Quanta 200 FEG scanning electron microscope (SEM) is a high resolution environmental microscope capable of running in high vacuum, variable pressure and environmental modes. This means that it can handle all specimens even uncoated, non-conductive samples as well as wet samples that require being above the vapour pressure of water. SEM also has the capability of detecting electromagnetic radiation in the form of X-rays and normal light near the visible spectrum, i.e. cathodo-luminescence (CL). This particular instrument was also obtained for its ease of use at very low electron probe energies, which is very useful for imaging specimens that cannot be conductivity coated properly. Typical SEM electron probe voltages vary between 5keV and 40keV. This instrument, on the other hand, can be used easily near 100Ev (Zhang *et al.*2003).

The degrees of freedom the operator has with instrumental parameters, include acceleration voltage, beam current, final apertures and specimen manipulation. In addition they include working distances between 5 and 48 mm, 360 degrees of rotation and 90 degrees of tilt. The degrees of freedom allowed within the specimen chamber imply that almost anything can be photographed with the resolving power attributable to electron beam instruments (Chong *et al.* 2002).

CHAPTER 4

EXPERIMENTAL PROCEDURE

This chapter gives a description of the sites where the sampling was carried out and indicates likely sources of emissions in the neighbourhood of the sites; this is followed by a description of the sampling procedure and that of the analysis of the data.

4.1 STUDY SITES

The sites which were selected for experimental procedures were the Rustenburg and Klerksdorp mining areas of the North West Province. According to the North-West Freight Transport Databank, Rustenburg is reported to be the fastest growing city in South Africa and is home to the two largest platinum mines and the largest platinum refinery in the world which processes 70% of the platinum mined in the world. Chrome is also mined extensively in the nearby town of Brits. Klerksdorp is mostly a gold mining town. Mining activities produce toxic metals like mercury, (Roulet *et al.*1999). Thus it is important to establish the contribution of particulate matter in the atmosphere in these two cities.

The State of the Air Report in South Africa (2005), lists polluting sources as industrial and commercial activities; electricity generation especially coal-fired and fuel-turbine power stations; waste treatment and disposal that includes incineration; residential activities that include burning of coal, paraffin, liquid petroleum (LP) gas, dung and wood; transport (petrol-diesel driven exhaust emissions, road dust raised by vehicles, etc); and agriculture. There are also contributions of particulate emissions from such activities as the incineration of waste from health institutions, boiler operations by industry and so on. Additions of health-risking particulate matter emissions into the environment by industrial giants like the mines are such that the public has raised complaints because of poor visibility and too much dust from smelters and refineries, as well as dust fallout from various tailings dams (Bullock, 2006).

Like many other settled areas of the world, Rustenburg as a mining city in the North West Province, has had the effects of human development on the quality of air. Before the onset of industrialization, the air in the town was influenced by natural phenomena and natural occurrences. Particulate matter in the atmosphere was a result of wind dust, fire-raised atmospheric aerosols and particulate matter emissions resulting from human activities. However, with the advent of increased population, pressures on the atmosphere also increased as a result of increased human needs. Increased population meant an increase in land use such as settlements, agriculture, and industry. Industrial developments in the form of mining have had more influence in increasing settlements in Rustenburg and the surrounding towns, just like in Klerksdorp (State of the Environmental Report Overview North West Province, 2002).

The air quality in the North West Province is dependent on emissions of pollutants from a variety of activities. The air quality has been affected by the change in population levels of the area and how the population has become distributed. Unplanned or informal settlements have arisen. These in most cases are of people in the low income group. Generally, the low income group people tend to use bio-fuels and the burning of wood for cooking purposes as well as for keeping themselves warm especially during winter. Low income groups engage in subsistence farming. Since they do not have adequate resources, their methods of preparing land contribute to the production and emission of particulate matter – especially during the burning of vegetation for clearing land. The household's use of coal, paraffin and Liquefied Petroleum Gas (LPG) as sources of fuel results in particulate matter being emitted into the air (State of the Environmental Report Overview North West Province, 2002).

The expanded economic activities promote an improvement of road network. Some roads are tarred and others are gravel roads. It is the un-tarred roads that are a major concern. They become a source of particulate matter emission as a result of the dust that is disturbed by both commercial and private vehicles – trucks hauling material from one place to another cause entailment of dust. Mechanical forces (between the tyre and the road surface) for example re-suspend particulate matter that had been deposited thereby

increasing aerosol particulates. Re-entrainment of deposited particulate matter can also occur as a result of air blown from vehicle exhausts pipes during operations.

Economic development leads to more vehicles on the roads with the result that particulate matter that eventually ends up in the atmosphere, thereby degrading its quality, is produced by both diesel and petrol vehicles. Miscellaneous sources of emissions of particulate matter that could be considered are the burning of tyres and dust generated at construction sites. The mines themselves have a number of activities that produce particulate matter and pollution that is dangerous to communities especially those that live within areas where mining takes place. Some examples of such activities include operations in the open cast mines, blasting activities, crushing activities, waste discarded as rock dumps, slimes and tailings dams (State of the Environmental Report Overview North West Province, 2002).

The two sites where the sampling procedure was performed were, Botshabelo Community Health Center in Khuma (Klerksdorp) and Impala Mines in Rustenburg. The Botshabelo Community Health Center is located between longitude $26^{\circ} 50' 47.1''$ south and latitude $26^{\circ} 51' 15.3''$ and Figure 4.1 shows its location in relation to surrounding mines. Figure 4.2 shows the location of the Impala Platinum mine, one of the biggest platinum mines in Rustenburg, and nearby areas such as the community of Luka.

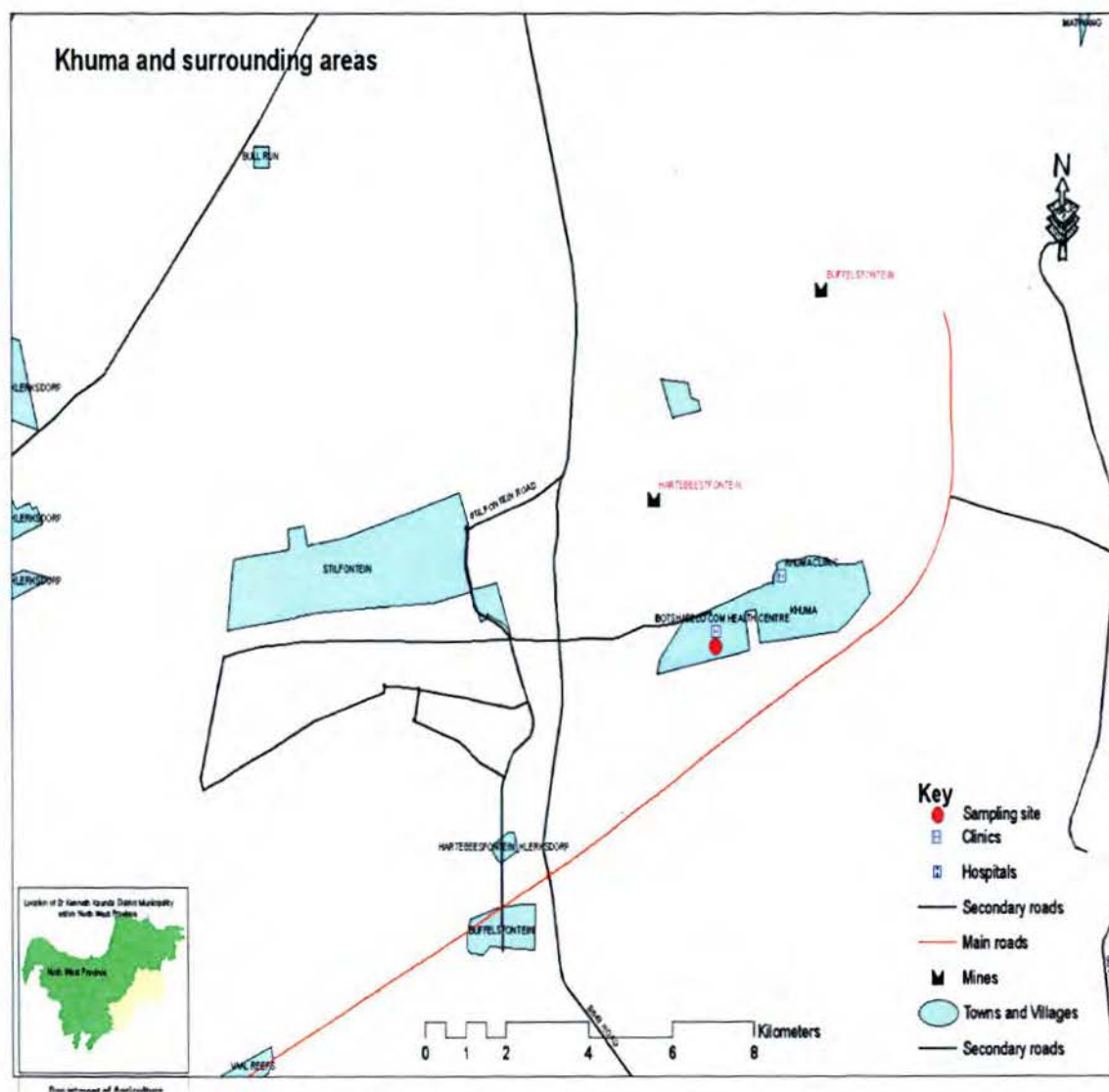


Figure 4.1: Location of Khuma and Jouberton study site in Klerksdorp

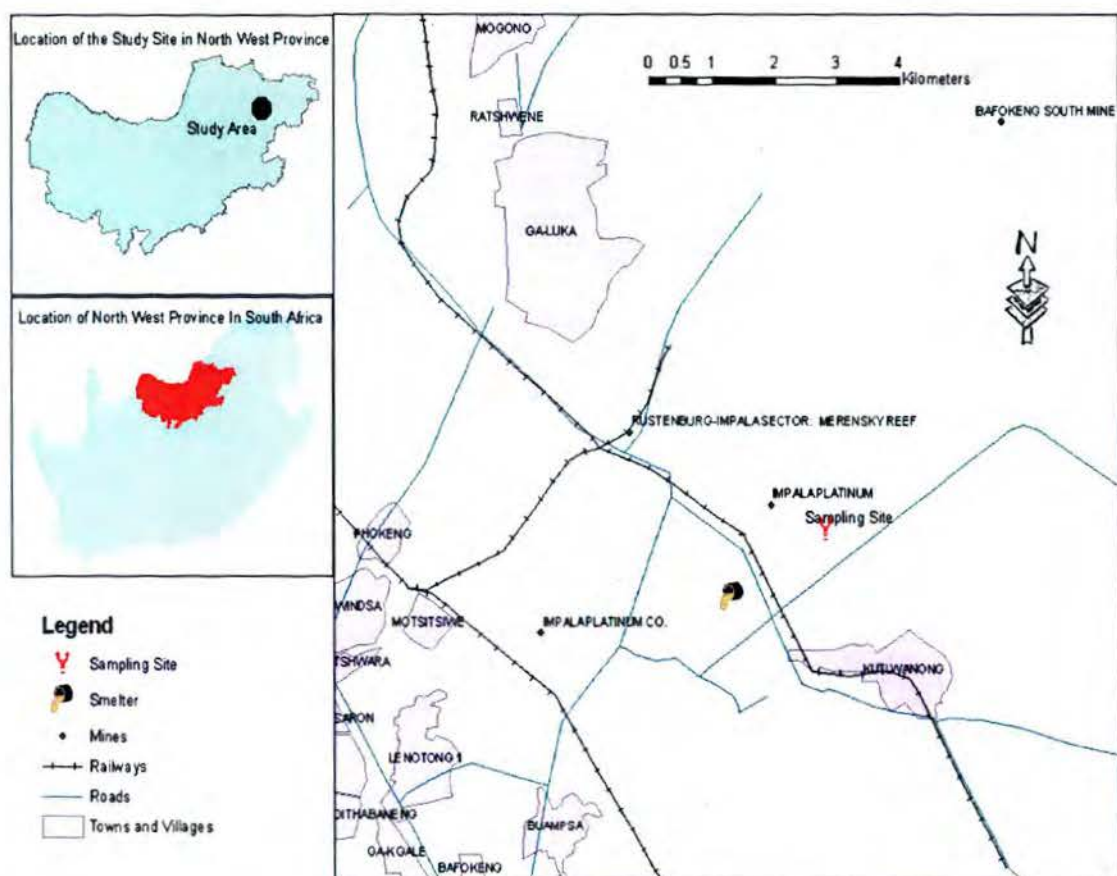


Figure 4.2 Location of Impala Mines study site in Rustenburg

4.2 SAMPLING PROCEDURE

The sampling procedure was done in three stages namely the pre-treatment of the polycarbonate foils filters, their weighing and the sampling of particles. The sampling exposure time for these studies was three hours. The pre-treatment consisted of the process of greasing the foils with an Apiezon-toulene mixture. The foils were in turn placed on a collection plate and fastened with a stainless steel holder ring while ensuring that there were no bubbles underneath the foil, and that no wrinkles appeared before the foils were greased. Figure 4.3 shows the greased filter within the holder ring. A brush was used to sweep the foils with the Apiezon-toulene mixture to grease it; taking care to ensure

that the greased filters did not touch the holder ring. This was achieved, by leaving a margin of approx 2-3 mm between the holder ring and the greased area of the foil. The grease was evenly spread on the foils and left to dry for at least 6 hours in a laminar flow chamber. This was done in order to ensure non-infection of foils before sample collection, and to remove the toluene from the foil so that only the grease was left. During the pre-treatment of filters, it was important to ensure that the collection plates and all other instruments used to handle them were clean. The tweezers used and the ring opener also needed to be clean. To this end plastic gloves were used and the foils were touched only with the tweezers.



Figure 4.3. Greased filter within cascade impactor holder ring

After 6 hours of drying, the second part was performed. For this part the collection foils were weighed with a Sartorius Analytic A 2005 electronic balance which is shown in figure 4.4. The weight had to be between 5.600-5.800 mg, depending on how much grease was on the foil. Foils whose weight was outside this range were not used.



Figure 4.4 Greased filter in the Sartorius Analytic A 2005 electronic analytical balance

The actual sampling of PM involved assembling and disassembling of the cascade impactor. First the uppermost stage was removed and joined to the inlet tube of the impactor, which was also the jet of the first stage. Next the filter was placed on a stainless steel screen with the rough side up. Then the first base plate was placed down over the filter. The rubber gasket (P/N TE-5018) on the bottom of the base plate fits around the periphery of the filter. A collection substrate was placed down on the base plate. Then the different impactor metal stages were placed down over the two threaded studs, starting first with the highest number stage. The impactor stages were assembled with their number in the upper right-hand corner. The slots on successive impactor stages were staggered so that each slot is above an impaction plate, not above another slot. The collection substrates were carefully placed between the collection plates so that the slots were exposed. The collection substrate was centred over the slots with the rough side up. The collection substrates for all stages were made in the same way.

Backup filters made of Teflon were used; these did not need greasing but were left inside the laminar flow chamber overnight to stabilize them with respect to water vapour in the laboratory.

During each measurement one backup filter and three greased polycarbonate foils were used. Care was taken to ensure that the assembling of the impactor took place in a laminar flow chamber free of particulate pollution (dust etc). First the backup filter was taken out of the petri-slide and placed inside the impactor. Secondly, the weighed and greased polycarbonate foils were taken out from a test tube and placed onto a collection plate. The stages were assembled putting the backup filter in first, then a spacer ring and a collection plate (PM<1), then a jet plate (PM1), then another spacer ring and a collection plate (PM2.5), and another spacer ring and collection plate (PM10). Lastly the impactor pump was connected onto the inlet as shown in figure 4.5.



Figure 4.5 Cascade Impactor attached on the pump

During the collection of data, the following were all recorded: start time – end time, date started – date ended, and gasometer start – gasometer end on the pump. For the pump to operate normally without any errors, the flow rate was set to be at 30 litres per minute. After the data collection, the mass and total volume of the gas were calculated to obtain the mass concentration in $\mu\text{g}/\text{m}^3$ (Maeuhaut *et al.* 2002).

The following data was recorded and used for this purpose:

Collection time	= End time – Start time (hrs).....	1
Collected mass	= End mass – Start mass (μg)	2

Total volume	= End gasometer – Start gasometer (m ³).....	3
Mass concentration	= Collected mass / Total volume (µg / m ³).....	4

4.3 CHEMICAL ANALYSIS OF FILTERS

The chemical analysis of the filters was carried out using an FEI Quanta 200 FEG scanning electron microscope. The ideal form of the sample for this spectrometer is one that is flat and polished. A flat, polished sample can move around on it in x and y motions without losing the optimum sample height for the X-ray optic. Samples prepared in metallurgical mounts are the most ideal type. This does not preclude using rough samples, only that it will require one to find the optimum sample height as the sample is moved from place to place.

Once the optimum stage height is determined by optimising the intensity and resolution on a higher energy x-ray line like CrKa or SiKa, the working distance (WD) is noted, and used as the reference for bringing other samples to the optimum height. If in the process of moving the sample to observe another region it gets out of focus, it is refocused using the z control of the stage.

Ideally, the sample should be mounted in a special holder so that the flat surface of the sample mount can be returned to the proper height by returning to a known z value of the stage. The reproducibility of this must be within a few microns to be useful. In general, when any type of analysis is being done, either a high magnification (> 5000x) or a spot mode should be used because of the limited field of view of the spectrometer.

4.3.1 Considerations for Quantitative Analysis

Quantitative analysis using a WDS spectrometer was performed in order to determine the k-ratios for each element. The k-ratio is the ratio of the intensity of the unknown divided by the pure element intensity measured under the same conditions of accelerating voltage and beam current. A k-ratio is determined for each element in the sample. The k-ratio is

to a first approximation, the weight fraction of the element in the sample. Sometimes it can be in error by a large amount depending on the matrix of the sample. In such cases the matrix correction procedure is applied to the k-ratio to correct matrix effects. In addition the standards of a known kV are measured. To measure the beam current, a faraday cage is used in conjunction with a Pico-ammeter. Important factors measured are the specimen heights of all measurements, the beam current measurements, the mode of scanning and spot or high magnification.

CHAPTER 5

DISCUSSION OF RESULTS

5.1. CONCENTRATIONS OF PARTICULATE MATTER

The results on concentrations of particulate matter (PM) in the Rustenburg and Klerksdorp (Khuma) study sites are discussed in this section. In Rustenburg the average time for sampling was 3 hours during day-time and the night-time sampling period for the study site was twelve hours (18:00 – 6:00). In Klerksdorp the sampling was done at 3 hours intervals between 09:00 and 15:00, and thereafter from 15:00 till 09:00 the following day mainly due to logistical problems and the results thereof will thus be presented only in the Appendix A. The meteorological data used for the study was provided by the South African Weather Services. The types of meteorological data obtained were temperature (°C), wind speed (m/s), wind direction and Pressure (hPa) at hourly intervals.

5.1.1 Concentrations of PM in Rustenburg

The mass concentrations of PM₁₀, PM_{2.5}, PM₁ and PM < 1 measured at the Rustenburg site are given in Table 5.1, while Table 5.2 gives the meteorological data of the same area for the same dates. The raw data for the meteorological data will be given in Appendix B.

Table 5.1: Mass concentrations of PM in Rustenburg ($\mu\text{g.m}^{-3}$)

Date	Time	PM 10	PM 2.5	PM 1	PM < 1
19/06	9:00 – 12:00	69.3	81.7	93.4	47.66
	12:00 – 15:00	44.4	29.19	41.44	37.48
	15:00 – 18:00	34.57	40.18	33.46	35.39
20/06	6:00 – 9:00	48	11.35	45.85	55.9
	9:00 – 12:00	37.82	35.36	31	39.57
	12:00 – 15:00	12.7	32.17	38.04	33.31
	15:00 – 18:00	42.19	41.81	39.85	34.96
	18:00 – 6:00	0.93	2.17	2.12	3.89
21/06	6:00 – 9:00	49.27	14.05	43.64	50.90
	9:00 – 12:00	36.53	35.40	33.02	35.44
	12:00 – 15:00	16.53	31.40	35.02	33.44
	15:00 – 18:00	46.72	38	35.14	34.32
	18:00 – 6:00	2.06	2.48	0.97	8.63
		32.65	7.84	5.97	31.32
22/06	9:00 – 12:00	30.60	24.84	28.56	32.14
	12:00 – 15:00	17.15	40	35.89	35.04
	15:00 – 18:00	39.16	30.47	11.53	35.56
	18:00 – 6:00	0.97	2.13	0.47	2.47
		38.68	36.34	33.85	38.08
23/06	9:00 – 12:00	31.64	11.79	13	33.21
	12:00 – 15:00	14.68	27.89	38.45	35.36
	15:00 – 18:00	12	7.38	23.80	31.70
	18:00 – 6:00	2.49	1.92	0.54	3.85
		31.64	40.55	15.78	41.82
24/06	9:00 – 12:00	37.71	37.32	33	34.89
	12:00 – 15:00	38.29	16.04	8.26	35.22
	15:00 – 18:00	6.68	7.54	12.86	35.25
	18:00 – 6:00	1.82	0.41	2.18	3.20
		19.39	39.83	11.57	41.87
25/06	9:00 – 12:00	34.54	3.39	41.88	38.5
	12:00 – 15:00	31.93	31.65	35.02	32.59
	15:00 – 18:00	33.71	4.8	38.41	34.29
	18:00 – 6:00	1.94	1.29	2.49	3.96

Table 5.2: Meteorological data for Rustenburg

Date	Start time	Temperature (°C)	Wind Speed(m/s)	Wind Direction	Pressure (hPa)
19/06	9:00	14.3	0.567	13	897.97
	12:00	19.5	1.6	25.667	895.57
	15:00	20.167	2.4	176.33	894.43
20/06	6:00	7.633	0.808	132.17	896.58
	9:00	4.033	1.633	232	897.53
	12:00	14.867	1.2	59	898.33
	15:00	18.433	1.433	43.333	896.27
	18:00	18.7	1	37.667	894.57
21/06	6:00	6.658	1.067	153.75	895.07
	12:00	14.5	0.9	12	894.9
	15:00	20.067	1.267	21	892.17
	18:00	20.367	1.733	324	890.07
22/06	6:00	7.625	0.658	99.667	890.67
	9:00	4	0.5	105	890.3
	12:00	16.833	1.7	141	890.47
	15:00	20.867	3.333	234.67	888.67
	18:00	19.667	3.3	244	888.03
23/06	6:00	9.675	1.842	102.42	890.99
	9:00	4.367	1.467	205.33	893.57
	12:00	12.4	0.833	53	895.4
	15:00	16.267	0.967	58	894
	18:00	16.533	0.733	125.33	893.13
24/06	6:00	4.575	0.75	94.583	820.57
	9:00	1.233	0.1	22	896.17
	12:00	13.1	0.933	20	897.07
	15:00	17.6	1.433	29.667	895.1
	18:00	18.4	1.433	244	893.37
25/06	6:00	4.1917	0.06	28	894.53
	9:00	6.5	1.7	152	895.63
	12:00	20.067	1.767	151	893.63
	15:00	20.2	1.167	109.33	892.67
	18:00	6.25	0.417	80.667	894.83

5.1.2 Day-time trends of PM concentrations in Rustenburg on weekdays

The concentrations for weekdays from Monday to Friday are shown in figures 5.1 (a) to (e). The equipment was set up on Monday in the morning so that data collection could only commence from 9:00.

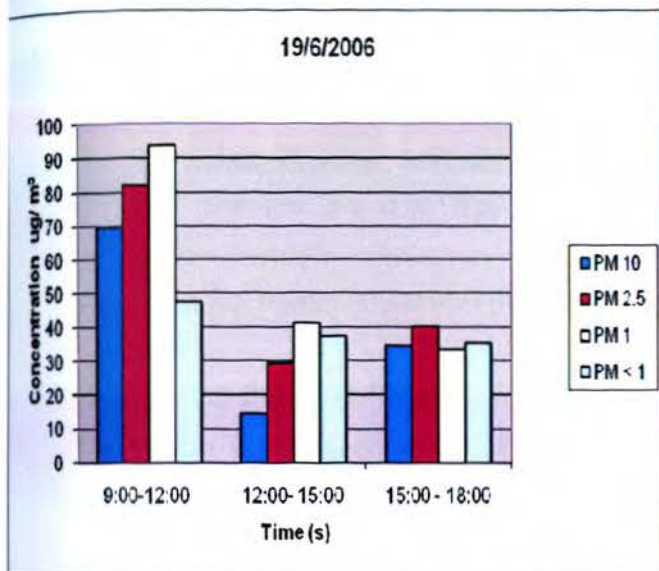


Figure 5.1 (a): Particulate Matter (PM) for Monday

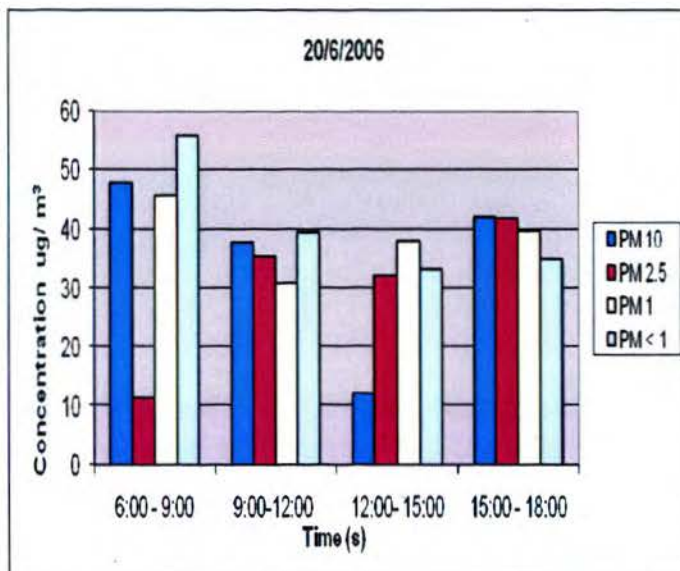


Figure 5.1 (b): Particulate Matter (PM) for Tuesday

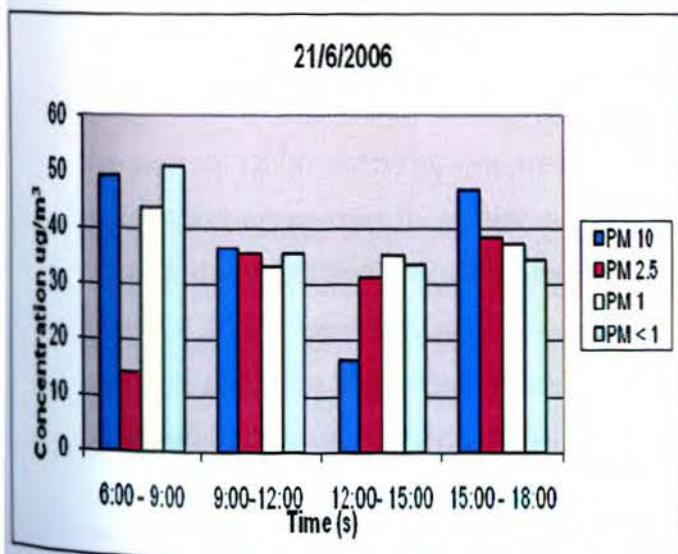


Figure 5.1 (c): Particulate Matter (PM) for Wednesday

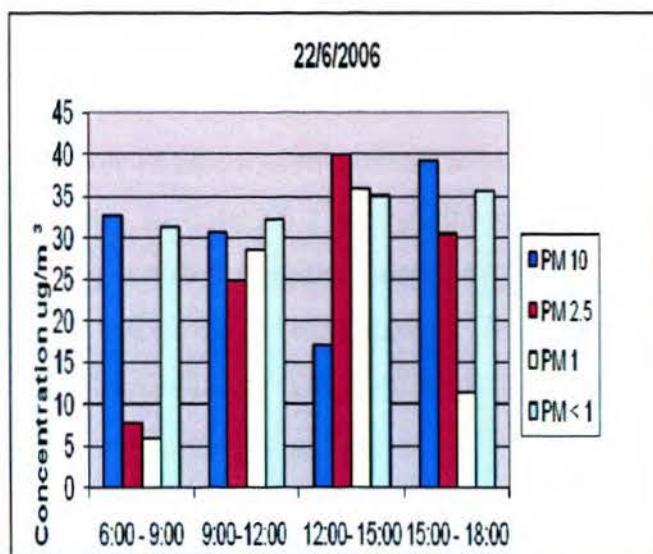


Figure 5.1 (d): Particulate Matter (PM) for Thursday

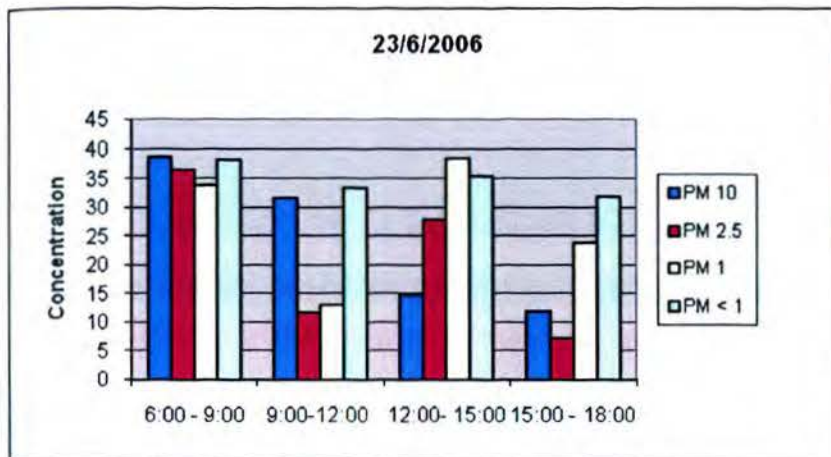


Figure 5.1 (e): Particulate Matter (PM) for Friday

Comparing the data found in figures 5.1 (b) and 5.1 (c) it is observed that all the PM levels follow the same sequence. PM 10 concentrations were high during the periods 6:00 – 9:00 and 15:00 – 18:00 in figures 5.1 (b) to (d). This is likely to be a result of increased human activities in the vicinity, such as cooking, going and coming back from work etc, during these times of the day. From Figure 4.2 which shows the map of Rustenburg where activities may be taking place, the measurement site is located about 500m from the road, 500m from a railway line, 1km from the impala platinum mine smelter and 2km away from a community settlement. The PM 10 concentrations show a decrease during the period 12:00 – 15:00, this trend can be a result of decreased human activities during this period compared to earlier or later in the day. In figure 5.1 (e), a similar pattern is observed except that PM 10 does not show as big a rise during the period 15:00 – 18:00. The PM 10 concentrations for these days were in the range 30 to 50 $\mu\text{g}/\text{m}^3$. These values are high although the peaks for the morning and afternoon are in the agreement with those obtained by Formenti (Formenti *et al.* 2004).

The PM 2,5 particles are lighter than PM 10 and can be influenced more by wind speed as to whether they settle fast or slowly. The concentrations of PM 2.5 from figures 5.1(b) to (d) start lower than PM 10 and rise during the day. This may be explained by the fact that these particles stay in the atmosphere longer than PM 10. The fact that this trend is not

observed in figure 5.1 (e) could be an indication of the influence of temperature, different wind patterns as well as differences in human activities on the particular day. All these factors can cause PM concentrations to deviate markedly from one day to another even though measured at the same time of day.

The fine particles in PM 1 stay long in the air. The concentrations of PM 1 from figures 5.1(a) to (d) are observed to be high, generally above $30 \mu\text{g}/\text{m}^3$. The PM <1 are also classified as fine particles, and their concentrations are observed to be generally high in the morning periods, as seen in figures 5.1 (b) to (e). This trend can be explained by the fact that these include even non-particles.

The results obtained show that PM 10 concentrations are higher than PM 2.5 concentrations. Similar results were also observed for PM10 and PM2.5 concentrations in studies carried out in Seoul in 2001 where concentrations of 79 and $47 \mu\text{g}/\text{m}^3$ respectively were found. The higher particulate concentrations in Seoul were a reflection of the relative dominance of anthropogenic sources (industry and traffic) that is why they were compared to this study.

The concentrations of PM 10 for both South African Standards and World Health Organization Standards are stated for 24hrs and for annual periods. In view of the fact that in this study the concentrations were measured for three hours not 24hrs, a direct comparison cannot be made.

5.1.2.1 Impact of Meteorological factors (on Tuesday) of PM concentrations in Rustenburg

The discussions of the impact of meteorological factors on PM concentrations were done for one day during the week and one day during a weekend, and relevant data is given in figures 5.1 (f), (g) (j) and (k). Meteorological data for the other days is given in the Appendix B.

Figures 5.1 (f) and (g) show wind speed and wind direction respectively.

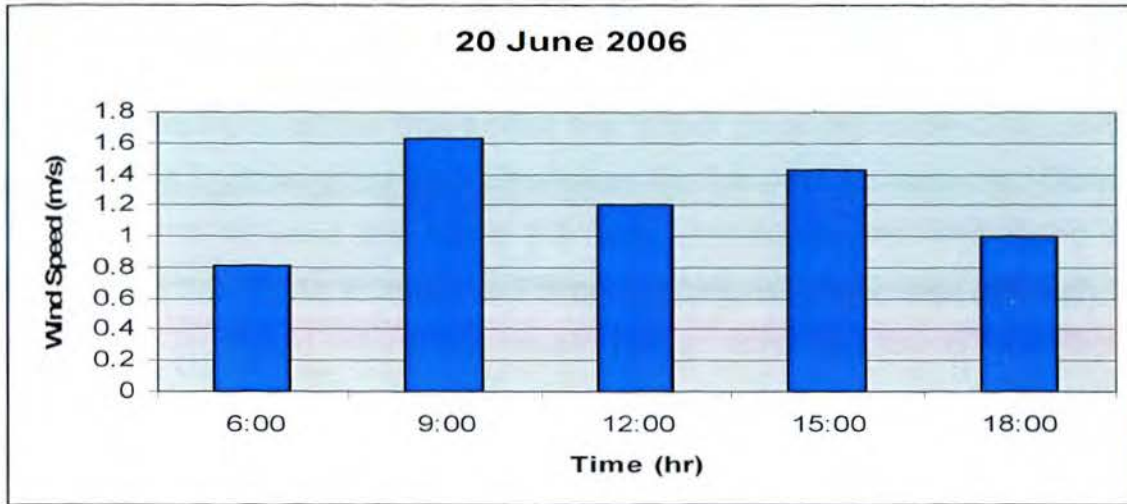


Figure 5.1 (f) Average wind speed on Tuesday 20 June 2006

The wind direction in the morning of Tuesday 20 June at 9:00 was south-westerly (232°) as shown in figure 5.1 (g). From Figure 4.2 it is observed that this is the direction of the smelter, a railway line, a road and some human settlements. The wind speed at this time was high at 1.7 m/s so that this could result in high concentrations being determined for all particle sizes in the morning, and this is seen to be the case for the period 9:00–12:00 in figures 5.1 (a) to (d).

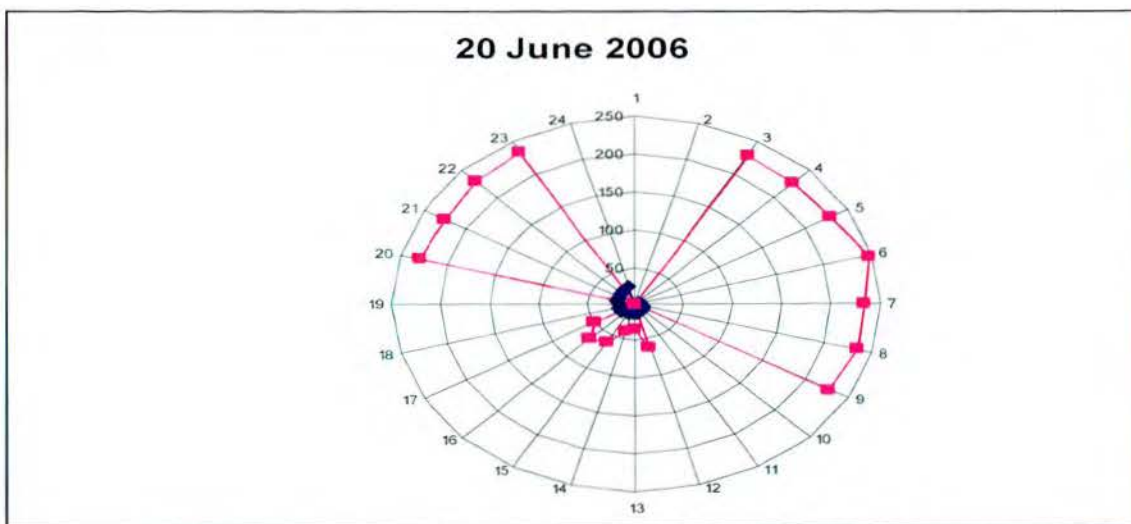


Figure 5.1 (g) Average wind direction on Tuesday 20 June 2006

At 12:00 the wind rose of figure 5.1 (g) shows that the wind direction was north-easterly (59°) and the wind speed was still high at 1.2 m/s. It is also observed that PM 10 concentration had decreased at this time. This suggests that the production of the coarse particles is reduced at this time or that it is further away in this direction, as can be seen from figure 4.2, although the high wind keeps the fine particles airborne. During the period 15:00 – 18:00 the wind direction is still north-easterly and the wind speed still relatively high (over 1.0m/s). As a result the PM concentrations remain high although this time PM 10 has also increased reflecting increased human activities which is most likely to be road transport.

Standard wind patterns may deviate markedly due to varying frictional effects of the earth surface such as rural open land, irregular topography, urban development and the effects of radiant heat from the city. In addition the variation of the horizontal wind speed with height is important in evaluating diffusion from stacks, while close to the ground the effects of friction retard the wind flow and cause it to change the direction as well.

5.1.3 Day-time trends of PM concentrations in Rustenburg on a weekend

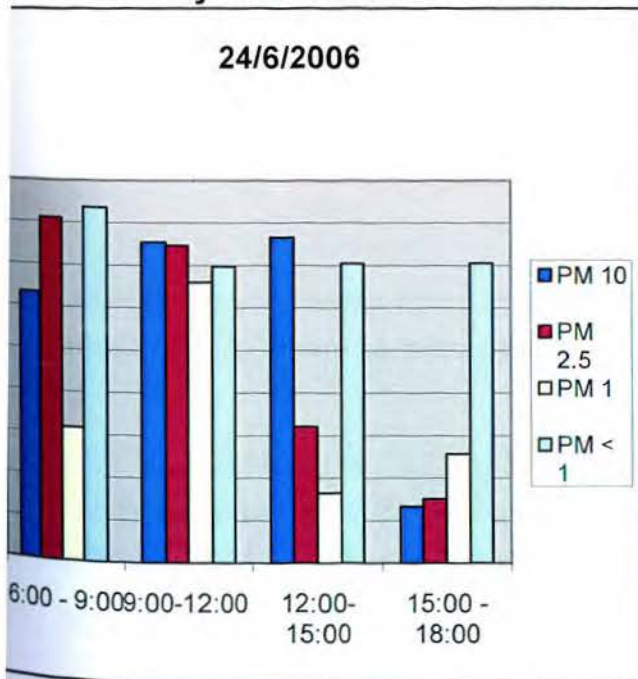


Figure 5.1 (h): Particulate Matter (PM) for Saturday

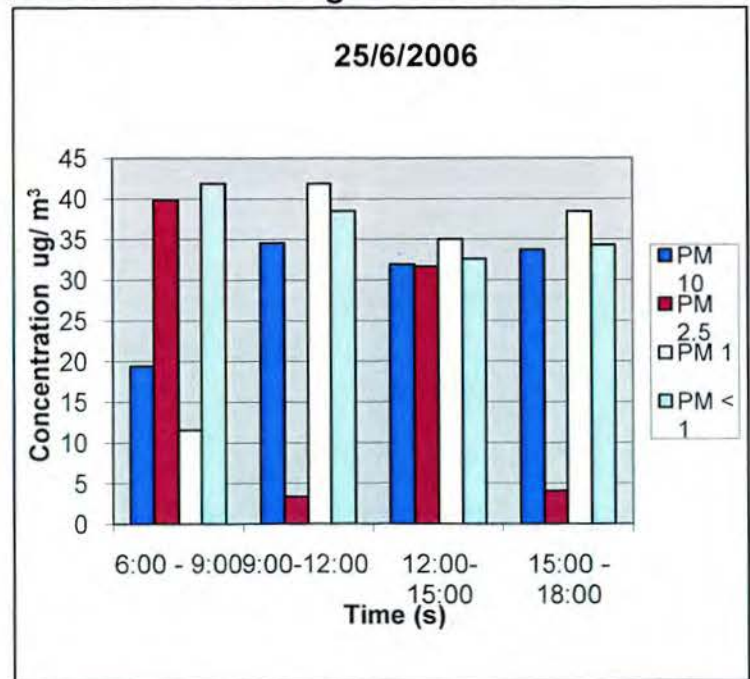


Figure 5.1 (i): Particulate Matter (PM) for Sunday

In figures 5.1 (h) and (i) the weekend particulate matter for Saturday and Sunday are shown. For the period 6:00 – 9:00 the trends for PM are similar on both days. It is also observed that the concentration of PM was generally low compared to that obtained during weekdays. The PM concentration on Sunday during the period 12:00-15:00 was high suggesting that an episode occurred. The high concentration can be caused by burning of tyres, veld fires, and domestic burning and cooking. The lower concentration is attributable to less industrial activities happening on the weekends.

5.1.3.1 Impact of Meteorological factors (on Saturday) of PM concentrations in Rustenburg

Figure 5.1 (j) shows the wind speed to be 0.7 m/s in the morning and it dropped to 0.1m/s by 9:00.

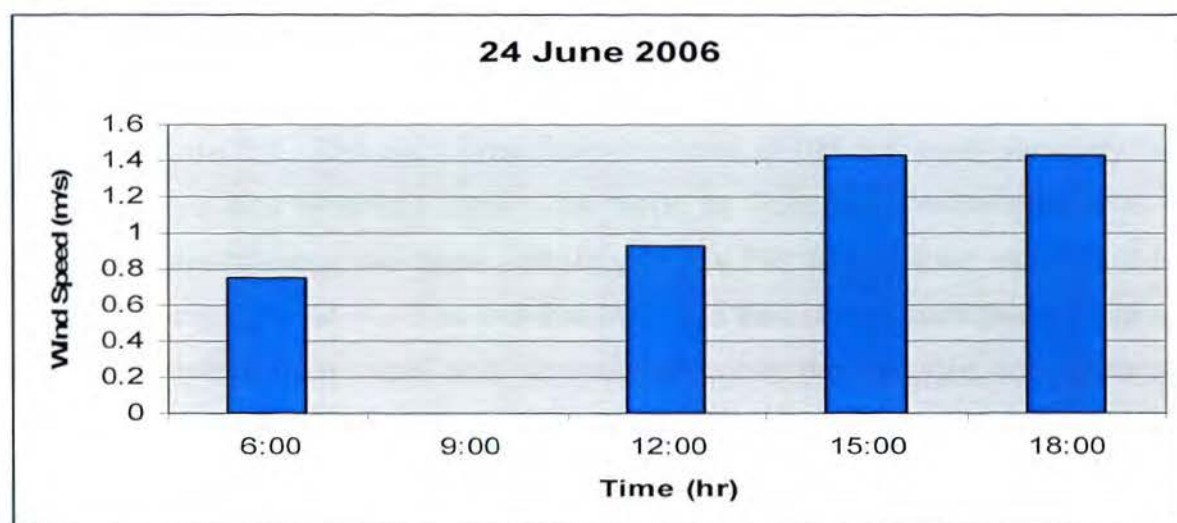


Figure 5.1 (j) Average wind speed on Saturday 24 June 2006

The wind direction as recorded in Table 5.2 came from the easterly direction (94°) during morning period until the afternoon. This is the direction of a nearby road. The wind direction had changed to 22° by 9:00, and this is the direction in which possible sources are relatively far from the measurement site. The fact that PM 10 is high at this time despite the low wind speed could be a result of an episode occurring to generate PM, but it could also be due to the low pressure recorded at that time. The pressure affects PM in that when it is low, air upliftment by convection is more likely to occur. The effect of

temperature on PM concentration depends on the composition of the PM. It can increase the formation of PM by increasing the oxidation rates of sulfur dioxide, nitrogen oxides, organic compounds and by increasing the concentration of oxidants in the air. On the other hand it can also reduce PM formation if it shifts the particle phase of more volatile compounds, e.g., nitrate and volatile organic compounds to the gas phase. In the morning the low temperature of about 4°C was unlikely to affect formation and removal of particulate matter. However, by the afternoon the temperature had risen to 13° and above thus favouring an increase in PM₁₀ concentration. To assess the impact of each of the meteorological parameters on the PM would require the use of multivariate statistical analysis which was not part of the present study.

5.1.4 Night-time trends in PM concentrations

The night-time concentrations of particulate matter for the period 19 -25 June 2006 are shown in figure 5.2. The night-time concentrations of PM < 1 were generally high for all the weekdays and weekend days. The trend in Tuesday, Wednesday and Thursday concentrations followed the same pattern with low PM₁₀ and then high PM_{2,5} and low PM₁ and very high PM<1. The fact that there are less coarse particles at night correlates with low activities from roads and communities, while the elevated concentration of fine particles especially PM <1 indicates the longer time these particles take to settle. Weekends concentrations, Saturday and Sunday, also have similar trends but different from those on the weekdays. During the weekend coarse particle (PM₁₀, PM_{2,5}) are lower than finer particles (PM₁, PM< 1).

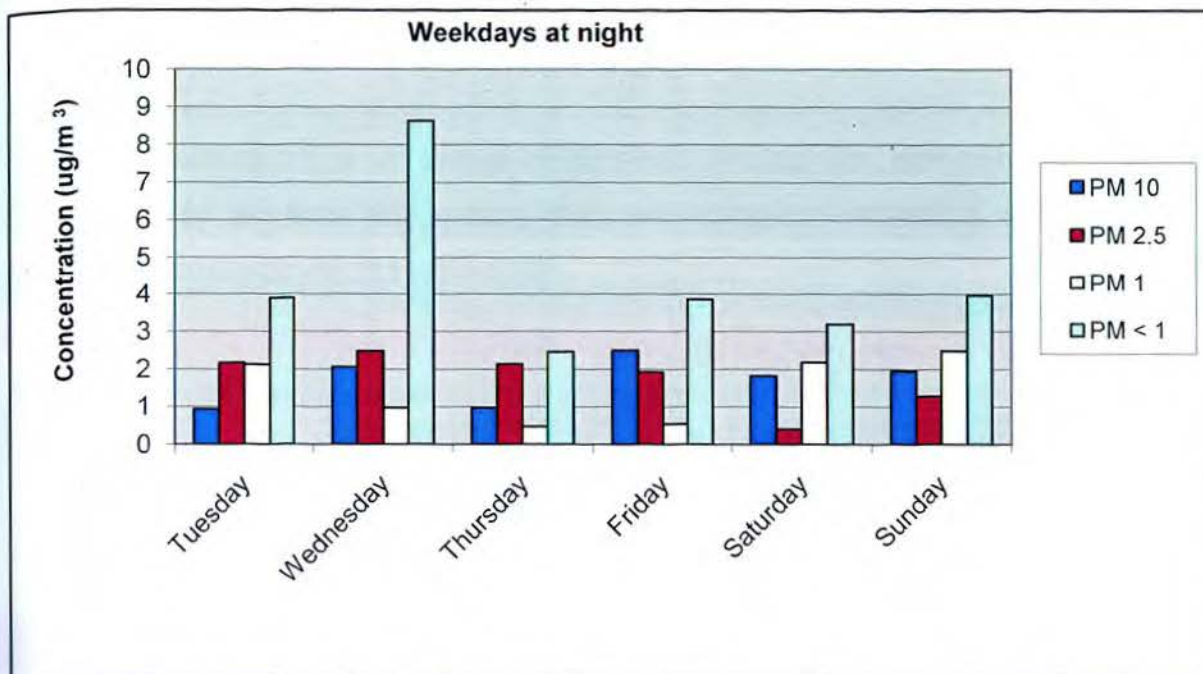


Figure 5. 2: Particulate Matter (PM) for Night-time from 18:00 – 06:00

The highest night-time concentration measured during this week was found to be 8.5 $\mu\text{g}/\text{m}^3$ for PM< 1. This may be caused by particles not settling during the day during the cold winter season with its low temperatures..

PM for the night-time could not be compared to day-time concentrations because the time taken for measuring the PM at night was from 18:00 – 06:00, (12 hours) whereas during the day-time the concentrations of PM were measured over periods of 3 hours.

5.1.5 Weekday v/s Weekend PM Concentrations at Daytime

PM concentrations were higher during weekdays than on weekends as shown in figure 5.3. Looking at Monday, Tuesday and Wednesday in the mornings, the concentrations were very high compared to those obtained at the weekend. This is to be expected because during the weekdays the emissions are from different sectors:- primary, secondary, fugitive, slag and vehicle emissions. During weekends there are fewer activities from mines, vehicles and fewer people going to work. In addition the emissions

from local fuel stations, domestic emissions like burning of waste are reduced during weekends. The difference is, however, not that huge, possibly due to fact that the underground mines which produce fugitive emissions operate 24 hours. Furthermore, since Rustenburg is a tourist destination having, for example, game reserves and community activities this means that anthropogenic emissions may not necessary be greatly reduced over the weekends.

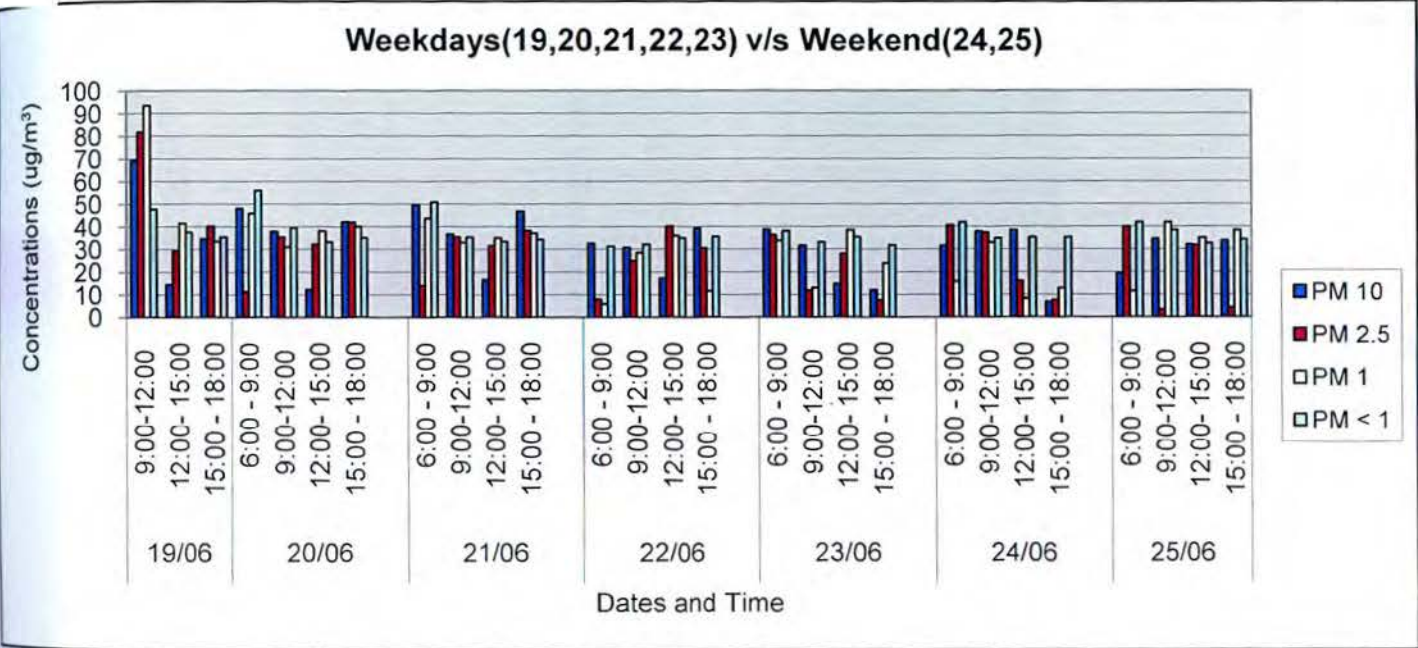


Figure 5.3: Particulate Matter (PM) for Weekdays and Weekend

5.1.6 Weekday v/s Weekend PM Concentrations at Night-time

The night-time concentrations of particulate matter for weekdays and weekends are shown in Figure 5.4. It is clear from the graph that the fine particles of PM <1 have a higher concentration both during the week and during the weekend.

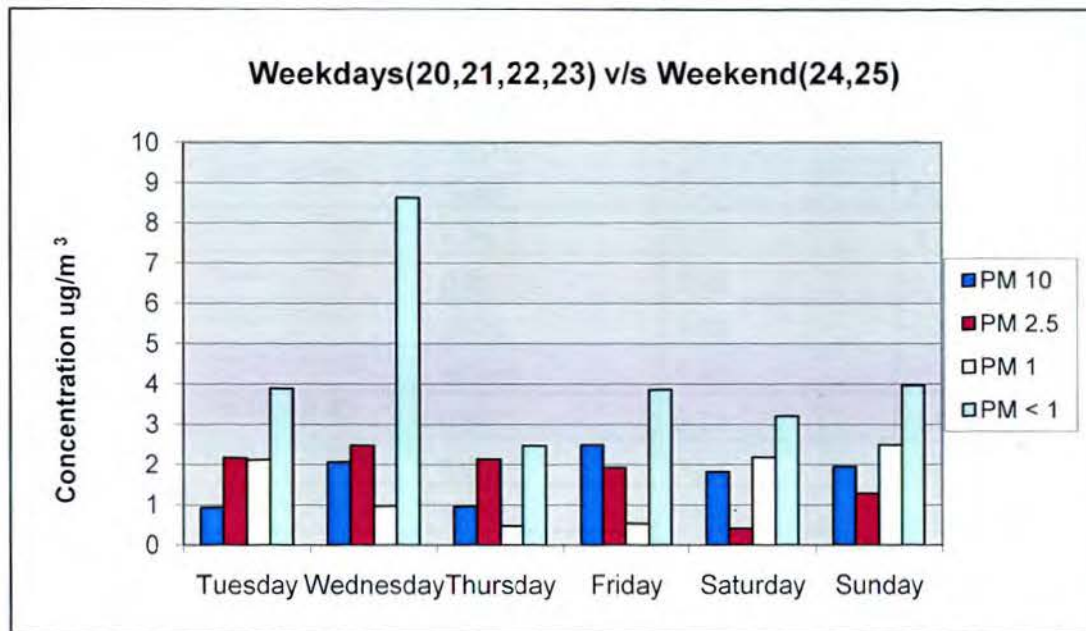


Figure 5.4: Particulate Matter (PM) for night- time weekdays and weekends

By adding all the concentrations of each day, it is found that the weekday values are generally higher than weekend values. The difference is however, not large again as a result of the fact that those entities which have 24 hours operations would do so on weekdays and weekends.

5.2 PARTICULATE MATTER IN KLERKSDORP

5.2.1 Concentrations of PM in Klerksdorp

The concentrations of PM 10, PM2.5, PM1 and PM < 1 levels at the Klerksdorp (Khuma) site are reported on Table 5.3. The data was collected during winter from the end of May

to the beginning of June. Due to logistical constraints the site in Klerksdorp could not have sampling done during the periods from 6:00 to 9:00 and from 15:00 to 18:00 as was done at the Rustenburg site. The average time for sampling was 3 hours which was from 9:00 to 12:00 and from 12:00 to 15:00. While these results are discussed for a week, the rest of the data are given in Appendix A (b).

Table 5.3 : Mass concentration of PM in Klerksdorp($\mu\text{g.m}^{-3}$)

Date	Time	PM 10	PM 2.5	PM 1	PM < 1
29/5/06	9:00 – 12:00	12.58	7.21	40.25	37
	12:00 – 15:00	4.14	8.03	9.79	31.58
	15:00 – 8:00	0.26	0.49	0.16	1.89
30/5/06	9:00 – 12:00	29.79	1.05	1.59	32.20
	12:00 – 15:00	39.74	1.57	17.12	37.28
	15:00 – 8:00	0.81	0.28	0.12	1.33
31/5/06	9:00 – 12:00	3.27	32.8	5.96	35.02
	12:00 – 15:00	32.07	14.25	38.21	32.89
	15:00 – 8:00	1.09	0.94	0.53	1.96
1/6/2006	9:00 – 12:00	9.23	8.23	37.54	35.85
	12:00 – 15:00	10.29	8.43	6.68	3.18
	15:00 – 8:00	0.17	0.56	0.34	0.87
2/6/2006	9:00 – 12:00	7.14	1.39	38.93	11.46
	12:00 – 15:00	2.72	5.25	5.83	58.82
	15:00 – 8:00	0.14	0.96	0.55	1.81
3/6/2006	9:00 – 12:00	5.96	6.93	30.70	36.15
	12:00 – 15:00	42.26	2.07	3.59	33.59
	15:00 – 8:00	0.55	0.29	0.29	1.50
4/6/2006	9:00 – 12:00	47.26	37.87	35.17	39.30
	12:00 – 15:00	12.86	14.69	2.12	40.53

The meteorological data for the area is shown in Table 5.4. The data was used to explain the concentration variations observed during the study. The rest of the meteorological data is given in Appendix B (b)

Table 5.4 : Meteorological data for Klerksdorp

Date	Time	Temperature (°C)	Wind Speed (m/s)	Wind Direction	Pressure (hPa)
29/5/06	9:00 – 12:00	17.633	2.6	77	878.77
	12:00 – 15:00	22.367	1.833	73	876.63
	15:00 – 8:00	9.506	1.122	188.72	877.6
30/5/06	9:00 – 12:00	20.367	2.9	339.67	878.63
	12:00 – 15:00	24.9	1.667	75	876.5
	15:00 – 8:00	10.389	1.75	244.33	877.66
31/5/06	9:00 – 12:00	20.9	1.733	103.67	879.2
	12:00 – 15:00	25.067	2.533	158	877.47
	15:00 – 8:00	10.628	1.783	259.33	877.54
1/6/2006	9:00 – 12:00	20.733	1.433	315.33	878.57
	12:00 – 15:00	24	2.233	165	876.4
	15:00 – 8:00	10.194	1.55	206.67	876.14
2/6/2006	9:00 – 12:00	20.033	1.9	198	875.83
	12:00 – 15:00	24.467	3.5	208.33	873.57
	15:00 – 8:00	10.172	1.339	184.78	874.53
3/6/2006	9:00 – 12:00	15.6	1.7	89.667	877.83
	12:00 – 15:00	20.733	2.4	82	876.03
	15:00 – 8:00	10.611	1.956	68.278	879.33
4/6/2006	9:00 – 12:00	15.1	1.6	25	881.57

5.2.2 Day–time PM concentrations in Klerksdorp on weekdays

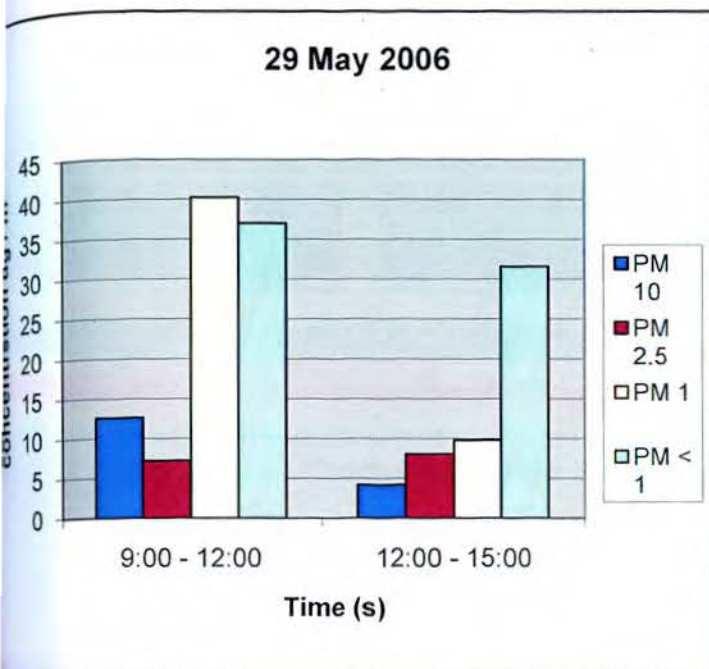


Figure 5.5 (a): Particulate Matter (PM) for Monday

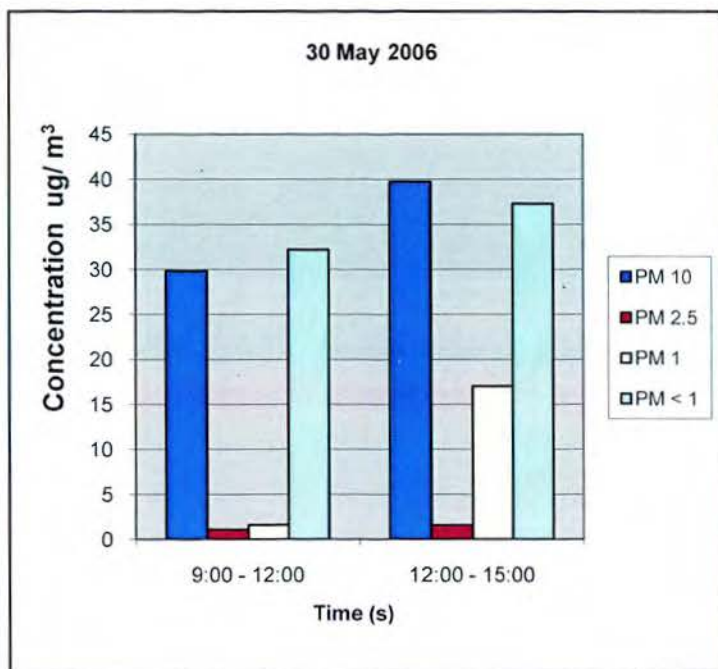


Figure 5.5 (b): Particulate Matter (PM) for Tuesday

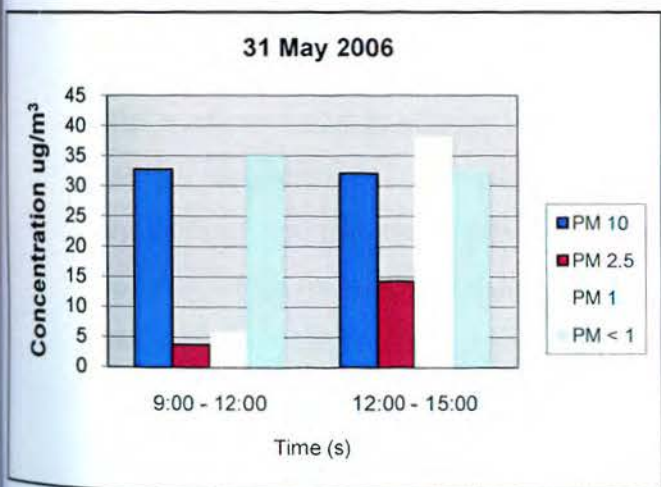


Figure 5.5 (c): Particulate Matter (PM) for Wednesday

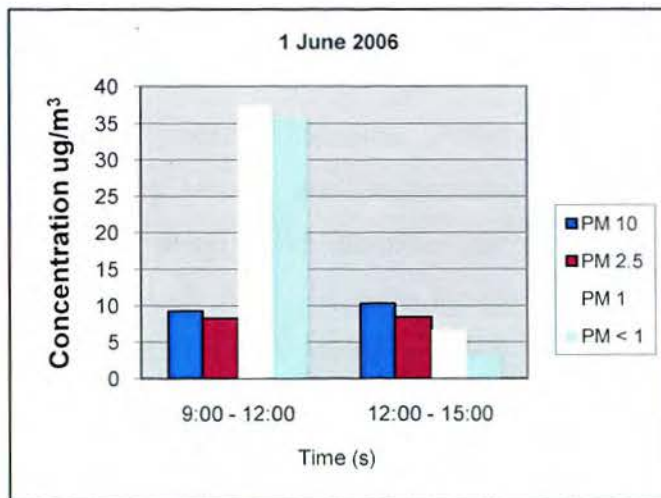


Figure 5.5 (d): Particulate Matter (PM) for Thursday

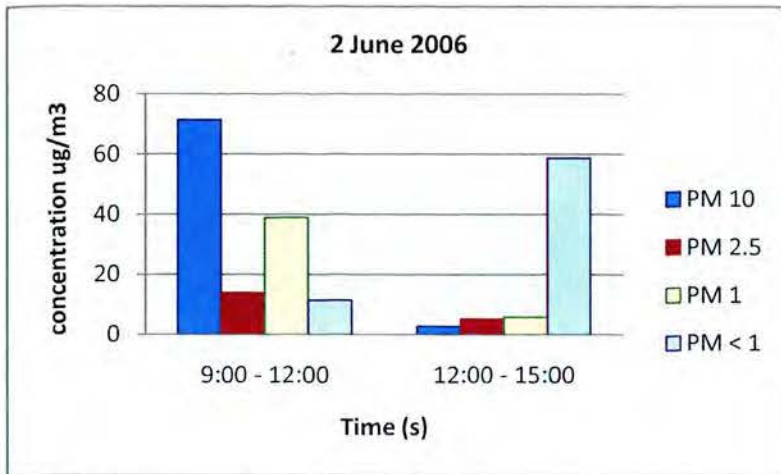


Figure 5.5 (e): Particulate Matter (PM) for Friday

Figures 5.5 (a) to (e) show the data for Monday to Friday, the weekdays. The concentrations of coarse particulate matter PM 10 are higher than those of PM 2,5 while for fine particles sometimes PM 1 is higher than PM < 1 and at other times PM<1 has the higher concentration. In order to relate the concentrations to human activities in the area, it is noted that the site is in the middle of a community area, in addition about 3.3km north-west of the site was a gold mine, a major road passes within 2 km to the south of the site, and a minor road is within 1 km to the north to north-west of the site. Peak times for vehicle movements and other activities like cooking which are responsible for the emissions are the mornings and evenings both of which were outside our sampling periods. This means that the samplings taken in this study relate more to the life-times of PM in air and to prevailing meteorological conditions rather than to its generation.

5.2.2.1 Impact of Meteorological factors (on Monday) on PM concentrations in Klerksdorp

The discussions of meteorological data will be done for one day during the weekdays namely Monday 29 May and one day during the weekend. The meteorological data is plotted in figure 5.5 (f) for wind speed and in figure 5.5 (g) for wind direction. The weekend data is plotted in figures 5.5 (j) and (k) for wind speed and wind direction respectively. The meteorological data for the other days will be given in Appendix B.

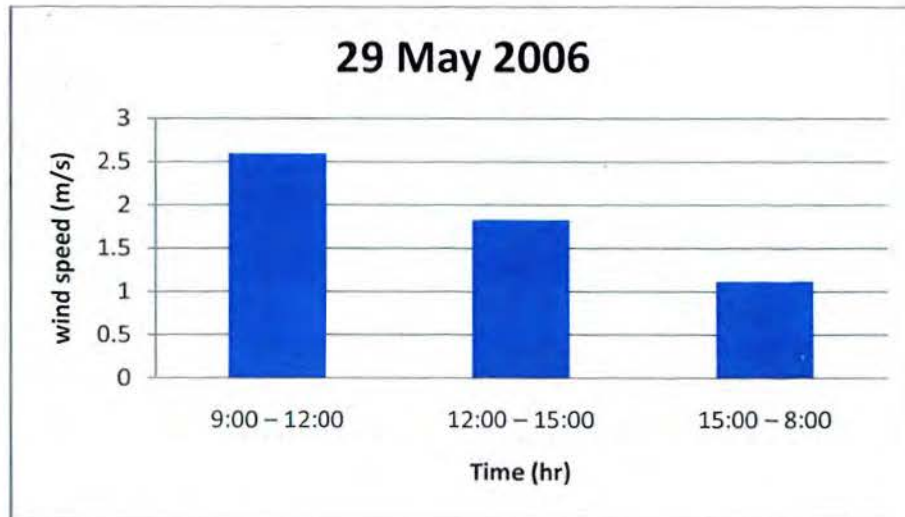


Figure 5.5 (f): Average wind speed on Monday 29 May 2006

The wind speed was high at 2.6m/s in the morning but decreased towards the evening. However, it was still high at 1.1 m/s.

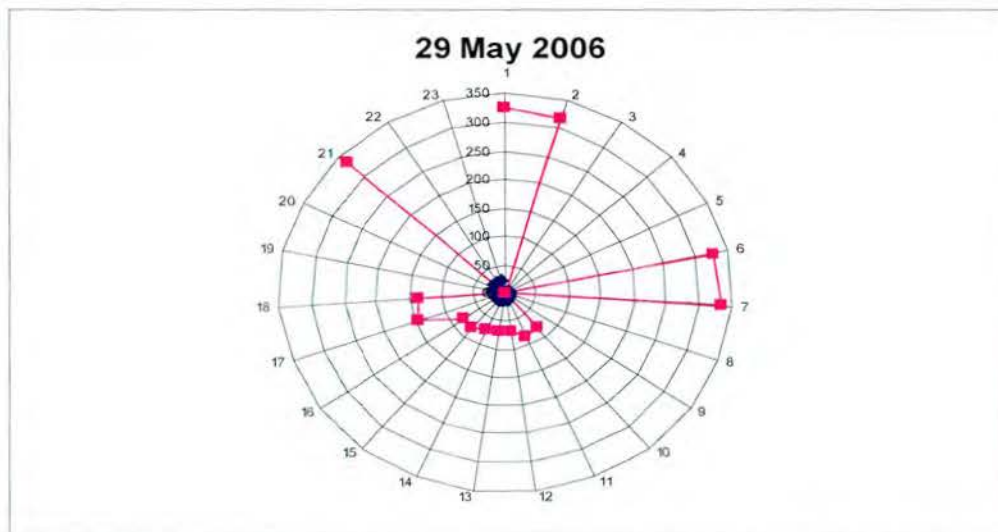


Figure 5.5 (g) Average wind direction on Monday 29 May 2006

The wind direction in the morning was north-east (77°). Figure 4.1 shows this to be the direction in which there is a major road nearby and minor roads further away. According to figure 5.5 (g), prior to the start of the sampling at 9:00 the wind came from the north-west

between 6:00 and 7:00, and this is the direction where there is another mine in the area. Since the pressure was low and therefore favourable for upward convection of PM, the temperature and wind speed were high. The observed concentration was influenced not only by road traffic but also by domestic, industrial and other gold mining activities in the surrounding areas of Orkney and Stilfontein.

It was found that PM < 1 is high in most sampling periods. This consists of fine particles that settle slowly and the sources may be industrial and other gold mining activities in the surrounding areas such as Orkney and Stilfontein. The busy road going to the Khuma area and to the mines some 60 meters from the study site are likely sources of the emissions. This road is used by commercial vehicles which transport people to and from Khuma for purposes of work in the mines, haulage trucks to and from the mines, as well as private cars.

5.2.3 Day-time PM concentrations in Klerksdorp on weekends

The Klerksdorp weekend concentrations obtained are in figures 5.5 (h) and (i). In both figure 5.5 (h) and figure 5.5 (i) the concentration of PM < 1 is high for both sampling periods. In figure 5.5 (h) PM 10 and PM 2,5 were slightly lower in the morning than in the afternoon. Also in comparison the coarse particles (PM 10 and PM 2.5) were low compared to fine particle (PM 1 and PM < 1). This may be caused by less activities on weekends around this period. Between 12:00 - 15:00 the PM 10 was the highest, with the other particle sizes (PM 2,5 and PM 1) much reduced as shown in figure 5.5 (h). The temperature decreased in the morning and high concentration were observed for fine particles on the 3rd of June and also high concentrations on the 4th June for both coarse and fine particles in the morning. From the observation it is evident that, when the temperature decreases the concentration increases.

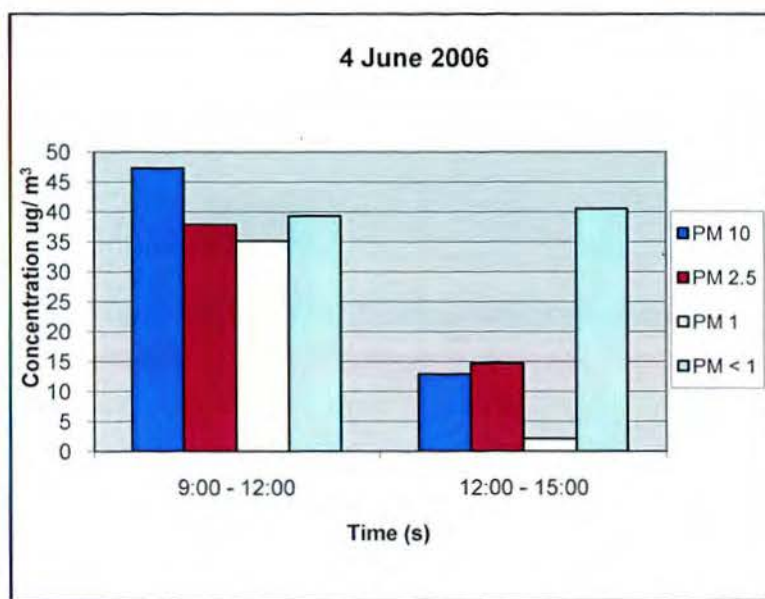
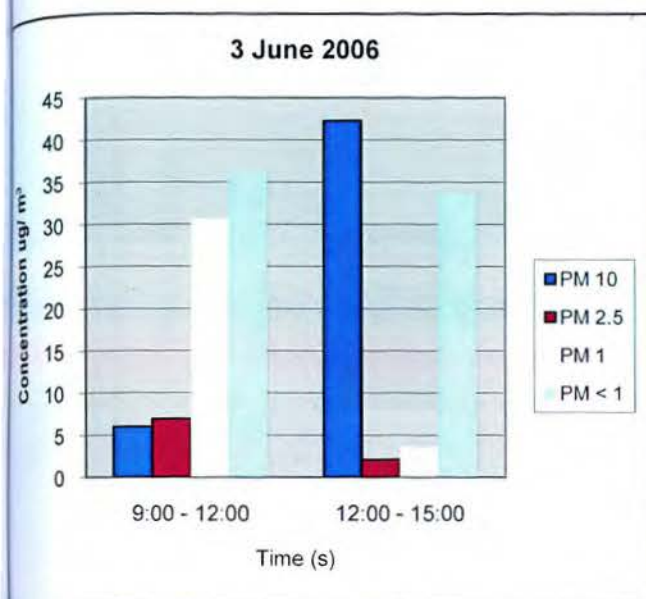


Figure 5.5 (h): Particulate Matter (PM) for Saturday

Figure 5.5 (i): Particulate Matter (PM) for Sunday

In figure 5.5 (i) the daily concentrations were generally higher between 9:00 and 12:00 than from 12:00 to 15:00. These trends are an indication that there are more domestic activities in the morning than later in the day which could be people preparing to go to church and using transport that cause vehicle emissions. The wind direction for both morning and afternoon on Sunday are between north easterly and south easterly. The high concentrations of fine particles are influenced by the re-suspension of pollutants and aerosols suspended in the air.

5.2.3.1 Impact of Meteorological factors (on Saturday) of PM concentrations in Klerksdorp.

The wind speed during the weekend (3 to 4 June 2006) was very high at more than 1 m/s and reached 2,4 m/s during the day. June 3 was windy almost throughout the day and this is shown in figure 5.5 (j).

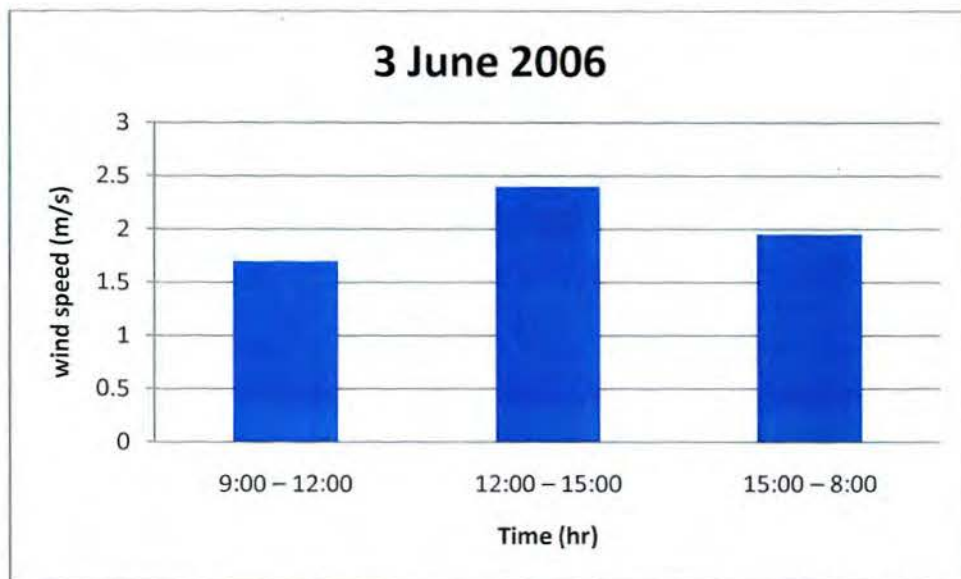


Figure 5.5 (j) Average wind speed on Saturday 3 June 2006

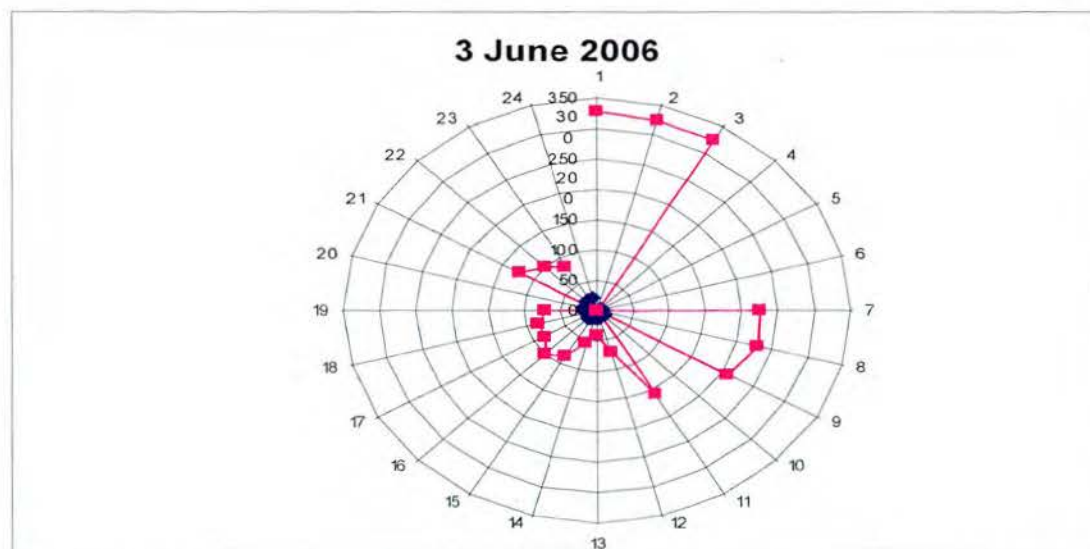


Figure 5.5 (k) Average wind direction on Saturday 3 June 2006

The wind direction as shown in the wind rose of figure 5.5 (k) is observed to have been from either south east or east during the sampling periods. According to figure 4.1 the likely sources could be domestic emissions from the neighbouring community settlements and the nearby road that passed within less than 2 km of the sampling site.

5.2.4 Weekday v/s Weekend concentration

Information on the weekdays and visas weekends concentrations of PM is an important indicator of the effects of domestic and industrial activities on concentrations. The concentrations of PM for Weekdays (29th May to 2nd June) and Weekend (3rd and 4th June) are shown in figure 5.6.

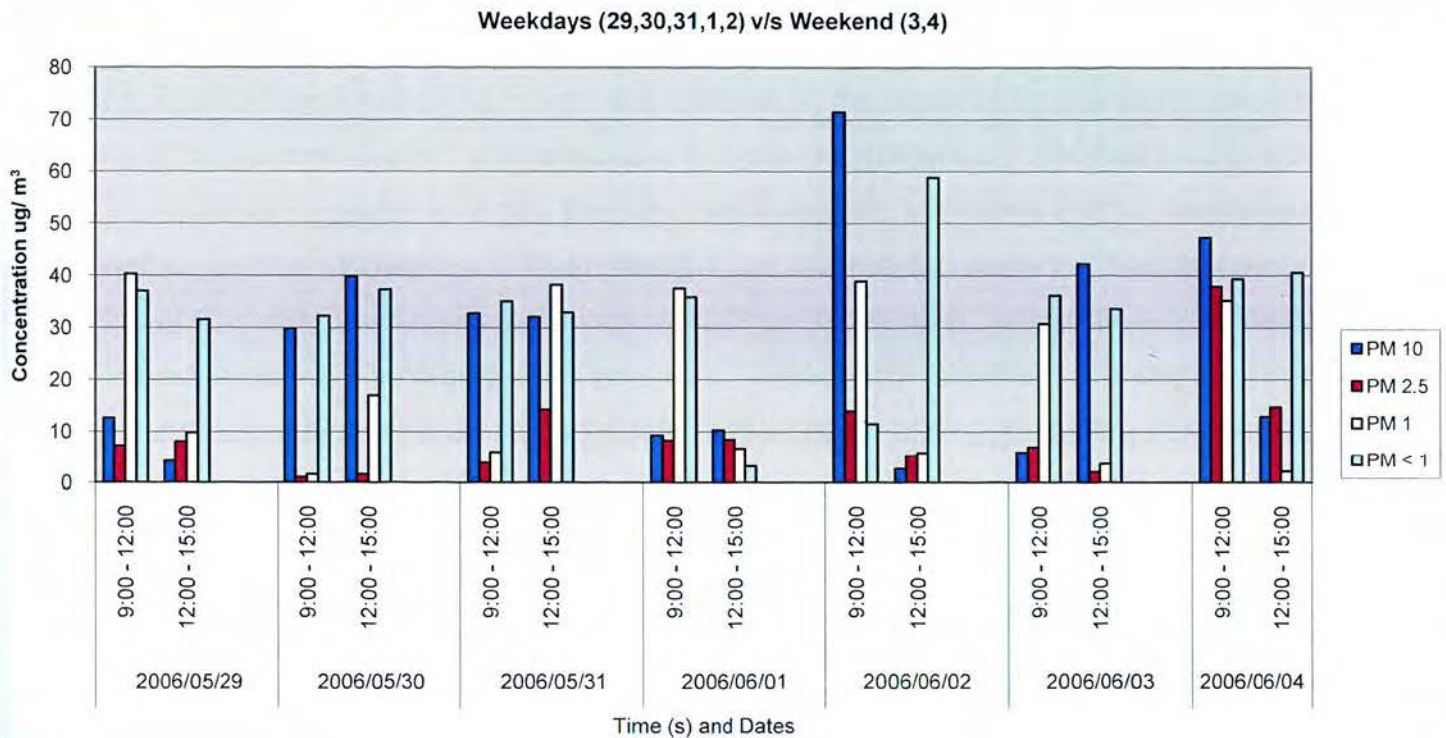


Figure 5.6: Particulate Matter (PM) on weekdays and weekends

The PM 10 and PM 2.5 concentrations were high during the weekend (3-4 June 2006) while PM 1 and PM < 1 were high during the weekdays (29 May - 2 June 2006). This indicates that the activities during the weekdays are linked to finer particles than the activities during weekends. The finer particles are indicative of fuel combustion sources from domestic and mainly industrial activities. The coarse particles are linked mainly to road dust caused by traffic and these are also fugitive emissions.

5.3 COMPARISON BETWEEN THE RUSTENBURG AND KLERKSDORP CONCENTRATIONS

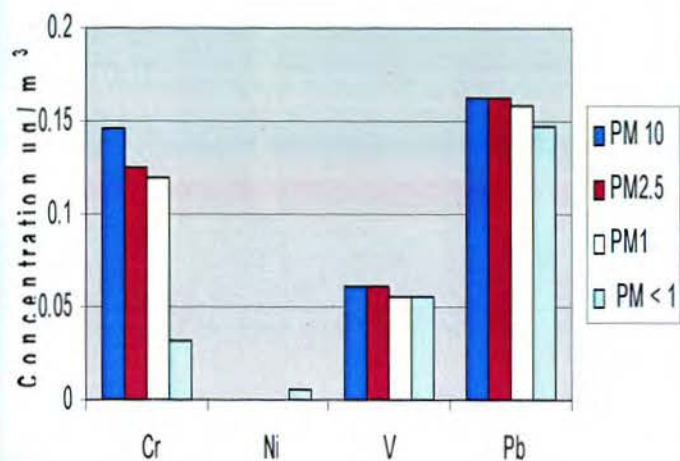
The PM concentrations were found to be higher in the Rustenburg study site than in the Klerksdorp site. The daytime PM levels went as high as $90 \mu\text{g}/\text{m}^3$ at the Rustenburg site while those at the Klerksdorp site were up to $55 \mu\text{g}/\text{m}^3$. The night-time concentrations ranged between $0.04 \mu\text{g}/\text{m}^3$ and $0.8 \mu\text{g}/\text{m}^3$ for Rustenburg, while those at the Klerksdorp study site were from 0.01 to $0.2 \mu\text{g}/\text{m}^3$. It is noted that Rustenburg was declared to be an air quality poor area and Klerksdorp was declared to be a potentially poor air quality area by the national department of environmental affairs on the National Air Quality Framework, Table 27 in the framework. The emissions in both the Rustenburg and Klerksdorp areas are mainly anthropogenic in origin; namely road transport, stationary combustion sources as well as mining. However, in Rustenburg there are more activities in that there is the mining of Chrome, granite and vanadium in addition to platinum, further there are open-pit mining activities that Klerksdorp does not have. These extra activities in Rustenburg could be the causes of higher levels of particulate matter. Apart from gold mining transportation is the biggest economy in Klerksdorp with big trucks always in transit through the town according to the North-West Freight Transport Databank.

5.4 ELEMENTAL COMPOSITION OF PM IN THE RUSTENBURG SITE

Elemental composition of PM was determined using PIXE for all elements but the main focus was on determining the occurrence and concentrations of the toxic elements: Vanadium (V), Chromium (Cr), Nickel (Ni) and Lead (Pb). The objective of this study was to determine the concentration of the toxic elements in different particle sizes.

5.4.1 Day-time Elemental Composition of PM in Rustenburg on weekdays

19 June 2006



5.7 (a): Elemental Composition for Monday

20 June 2006

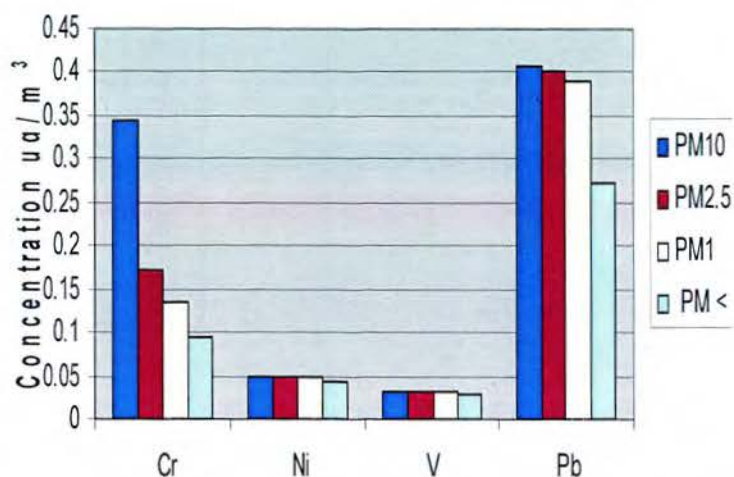
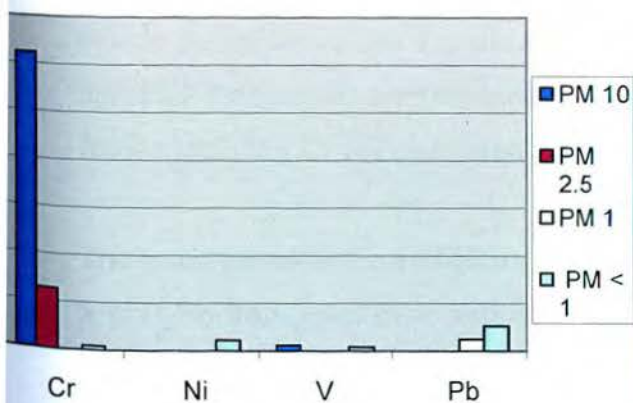


Figure 5.7 (b): Elemental Composition for Tuesday

21 June 2006



5.7 (c): Elemental Composition for Wednesday

22 June 2006

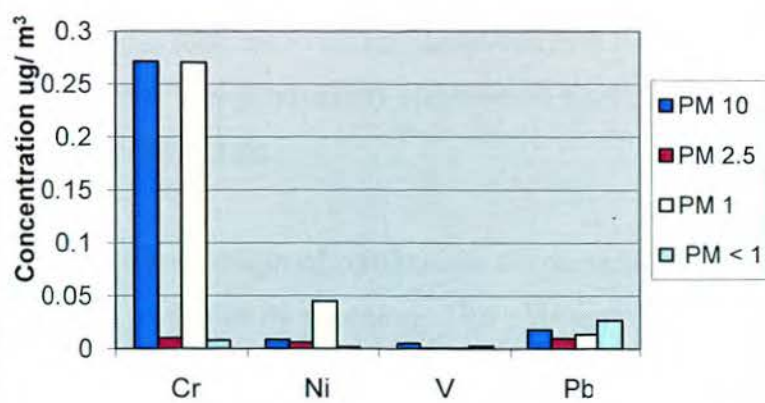


Figure 5.7 (d) Elemental Composition for Thursday

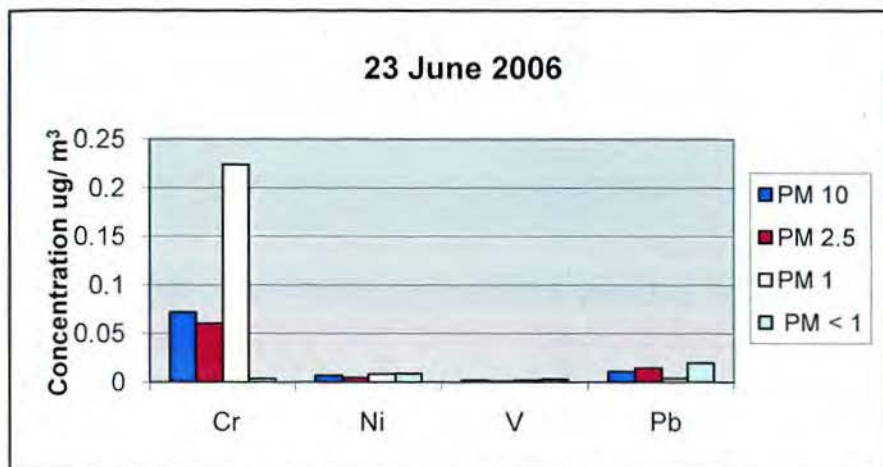


Figure 5.7 (e): Elemental Composition for Friday

Figure 5.7 (a) shows that Pb is the element with a high concentration in all particle sizes. This is followed by Cr which had a high concentration in PM 10, PM 2.5 and PM 1. Vanadium was also found to be present in all particle sizes while Ni was determined for PM < 1 only on that day. It is noted that on this particular day the wind speed was high from morning to about noon and it changed direction from south-east (102°) to north-west (205°) to north east (53°). From the location of the sampling site shown in figure 4.2, it is observed that vehicle emission from all around the mining areas from transportation of raw materials by the trucks and also the train contributed to the collected data. In addition, close to the sampling site there is a smelting operation and raw material is transported to two concentrator plants where it is milled. The milled ore is introduced to flotation banks where particles containing precious metals are separated as a concentrate leaving non-valuable tails which are deposited onto tailings dams. The production of platinum from the mines includes Cr which is also produced as part of the waste.

The occurrence of Cr and Ni indicates the anthropogenic origin of particulate aerosols with V and Pb from road dust and local traffic occurring in the early morning. The elements Cr and Fe may be the results of abundant ferrochrome mining activities in the Rustenburg emissions. Figure 4.2 shows that there is a road and a railway track on the south side of the sampling site which might have been the cause of the increase of emissions of Lead. Vanadium is also observed in all PM. With the wind coming from the south-easterly

direction, the emission could be influenced by a vanadium plant and from the burning of fuel oils on the east side.

In figure 5.7 (b) the highest elements identified were Pb and Cr with a concentration of $0.41 \mu\text{g}/\text{m}^3$ for Pb in PM 10, and a concentration of just below $0.35 \mu\text{g}/\text{m}^3$ for Cr. It is clear from the linking of the prevailing meteorological parameters and the PM concentrations already given that the toxic elements found in the emissions have the local industries as their main sources.

Figures 5.7 (c), (d) and (e) show that Cr is determined for PM 10, PM 2.5, PM1 and PM<1. In figure 5.7 (c) Cr concentration for the day is very high at $0.6 \mu\text{g}/\text{m}^3$ in PM 10, this is followed by PM 1 which had $0.12 \mu\text{g}/\text{m}^3$. Pb had a high concentration following Cr and in all particle sizes. This is due to the production of platinum where the element Pb is expected to be emitted by mine vehicles and trains which use fuels. Vanadium is also shown in small quantities and it is influenced by wind coming from north-east which is the direction of a vanadium mine. The high Pb levels for this study are between $0.01 \mu\text{g}/\text{m}^3$ and $0.2 \mu\text{g}/\text{m}^3$ while those of Cr ranged from $0.03 \mu\text{g}/\text{m}^3$ to $0.42 \mu\text{g}/\text{m}^3$ and these are in agreement with measurements obtained by (Kgabi *et al.* 2006) in Rustenburg.

The measured values for Cr during the week in figure 5.7 (a) to (e) did not exceed the limits of $1 \mu\text{g}.\text{m}^{-3}$ for NOISH and $1.5 \mu\text{g}.\text{m}^{-3}$ for APCEL; those obtained in this study were largely between $0.1 \mu\text{g}.\text{m}^{-3}$ and $0.6 \mu\text{g}.\text{m}^{-3}$. Cr had high concentration levels even though the standards were not exceeded. Pb did not exceed the WHO standard since it is $0.5 \mu\text{g}.\text{m}^{-3}$ and the lead concentrations found in this study were $0.41 \mu\text{g}.\text{m}^{-3}$. For V, the level of $1 \mu\text{g}.\text{m}^{-3}$ recommended by WHO was not exceeded since V had the lowest concentration on this day with less than $0.05 \mu\text{g}.\text{m}^{-3}$. While any level found in Ni is not safe, this was found to be $0.05 \mu\text{g}.\text{m}^{-3}$ on this day.

5.4.2 Day-time Elemental Composition of PM in Rustenburg on weekends

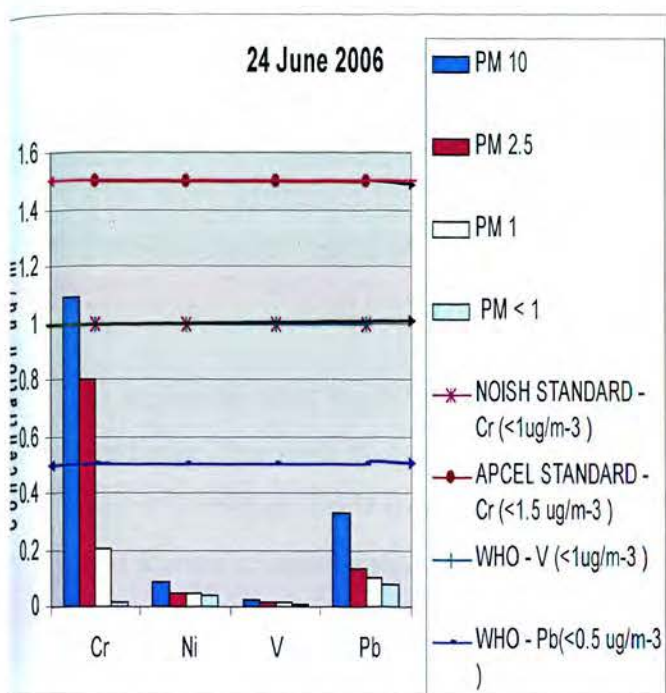


Figure 5.7 (f): Elemental Composition for Saturday

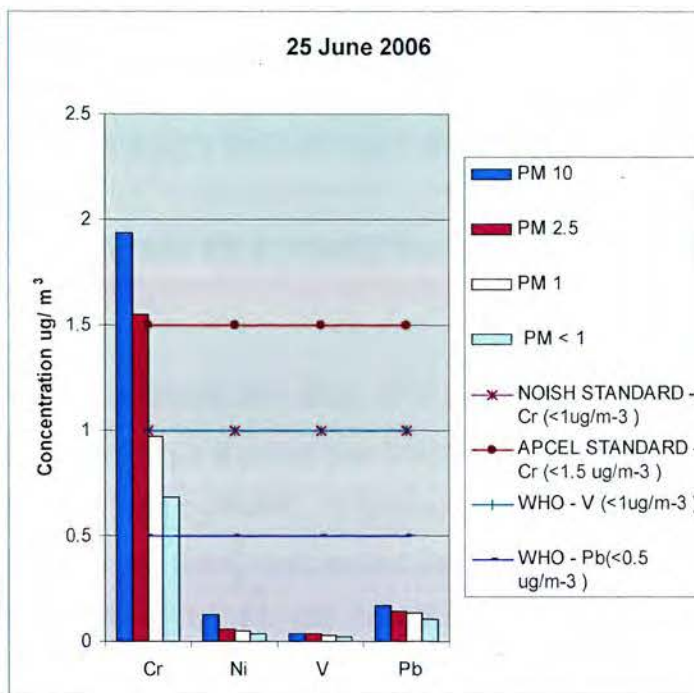


Figure 5.7 (g): Elemental Composition for Sunday

Figure 5.7 (f) shows the four toxic elements which were determined for all size particles on the weekend of 24th June. It shows that the concentration of Cr was high particularly in PM 10 and that it exceeded the NOISH standard. The Cr concentration in PM 2.5 was also high even though it did not exceed the standards. These results are consistent with those showed in figure 5.1 (h) which showed high concentrations of both PM 10 and PM 2.5 except during the 15:00 to 18:00 period. In figure 5.7 (g) the NOISH standard for Cr is exceeded in both PM 10 and PM 2.5. The wind speed on this day was 1.7 m/s and it came from the direction of a platinum mine, a ferrochrome mine and waste dumps. These Cr concentrations were identified for all mass size particles.

The high speed wind also came from the direction of (250°) which is the direction from the smelter of the platinum plant. The wind direction in the morning was 20° north-easterly and changed in the afternoon to north-westerly. In the vicinity of the sampling site are the community residence, road, railway track, a vanadium plant and a platinum plant on the

east side. The pollutants are therefore from the industries and mines, which cause the elements to be high for all the four toxic elements. On the weekend the wind speed was high in the afternoon and caused the particles to move in the north-westerly direction of (345°) and the PM 2.5 episode may have been caused by the waste dumping of chrome to the west of the site. Cr concentration levels were very high at more than $1 \mu\text{g.m}^{-3}$, and they were identified for all mass size particles. The occurrence of Cr with Ni indicates the anthropogenic origin of particulate aerosols with V and Pb indicating the contribution from road dust and local traffic.

In summary it is shown in figure 5.7 (f) that Cr exceeded the limits of $1 \mu\text{g.m}^{-3}$ for NOISH and also the limit of $1.5 \mu\text{g.m}^{-3}$ for APCEL. Pb did not exceed the WHO standard of $0.5 \mu\text{g.m}^{-3}$, neither did V exceed the levels of $1 \mu\text{g.m}^{-3}$ set by WHO. It is also noted that V had the lowest concentration on this day. In figure 5.7 (g) the Cr exceeded the limits of $1 \mu\text{g.m}^{-3}$ for NOISH but did not exceed $1.5 \mu\text{g.m}^{-3}$ for APCEL. Pb did not exceed the WHO standard of $0.5 \mu\text{g.m}^{-3}$ nevertheless lead concentrations were very high at $0.3 \mu\text{g.m}^{-3}$. The V levels of $1 \mu\text{g.m}^{-3}$ for WHO, were not exceeded and V had the lowest concentration of all elements on this day.

5.4.3 Night- time Elemental Composition of PM in Rustenburg on weekdays

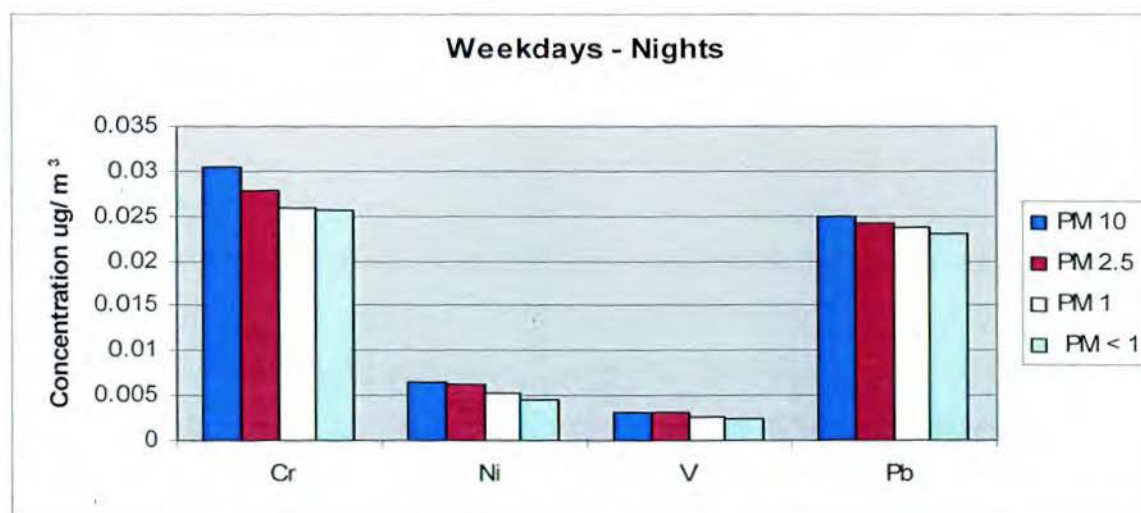


Figure 5.8: Elemental Composition of Particulate Matter (PM) for Weekdays Night - times

Figure 5.8 shows that the four toxic elements were identified in all particle sizes. The distributions of the metals in different size particles showed similar patterns but the concentrations of Cr and Pb were higher than those of Ni and V. Even though all the elements were identified, the amount of exposure was however low. This could have been as a result of some operations not continuing during the night. On the other hand there will still be road traffic; in addition waste dumps are not covered leading to transportation of aerosols by wind. The standards for all elements were not exceeded during night time for weekdays. This helps with regards to health considerations.

5.4.4 Night-time Elemental Composition of PM in Rustenburg on weekends

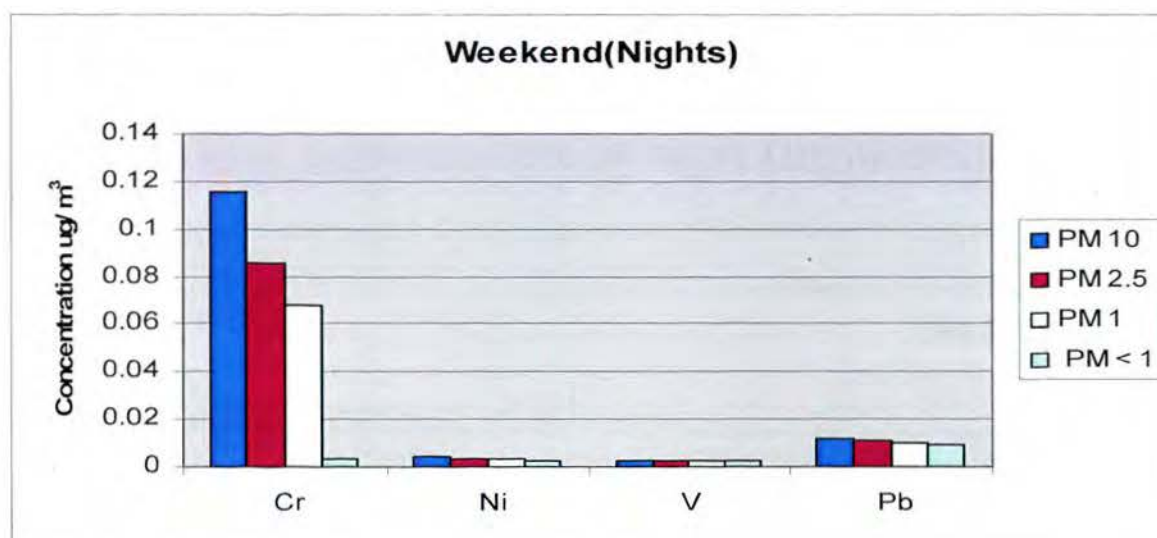


Figure 5.9: Elemental Composition for Particulate Matter (PM) for Weekend – Night

Figure 5.9 on the weekend concentrations shows that the concentrations were very high for Cr in PM10, PM 2.5 and PM1. With the wind direction of 244° which is the direction of a smelter relative to the sampling site, the smelter and waste dumps of platinum were likely emission sources. Cr had a night concentration of $0.1\mu\text{g}\cdot\text{m}^{-3}$, this was very high when compared to the concentration during weekdays and suggested that there could have been a different mode of operation during this period. All four toxic elements were observed in all particle sizes.

5.4.5 Day- time v/s Night-time Elemental Composition

The toxic elements Cr, V, Ni and Pb were identified during day-time sampling periods with Cr dominating. The Pb identified in the morning and afternoons maybe indicative of traffic. The night-time elemental levels were lower than day-time concentrations; which indicates that the elements are linked to domestic, vehicular emissions and industrial activities.

During weekends, the occurrence and concentration of Cr was higher than the other elements at night-time. The concentrations can be linked to the crustal deposits of Cr in the area as observed by (Kgabi *et al.*2006) in Rustenburg, which may be the result of long term (years) ferrochrome mining in the area.

5.5 ELEMENTAL COMPOSITION OF PM IN THE KLERKSDORP STUDY SITE

5.5.1 Day–time Elemental Composition of PM in Klerksdorp on weekdays

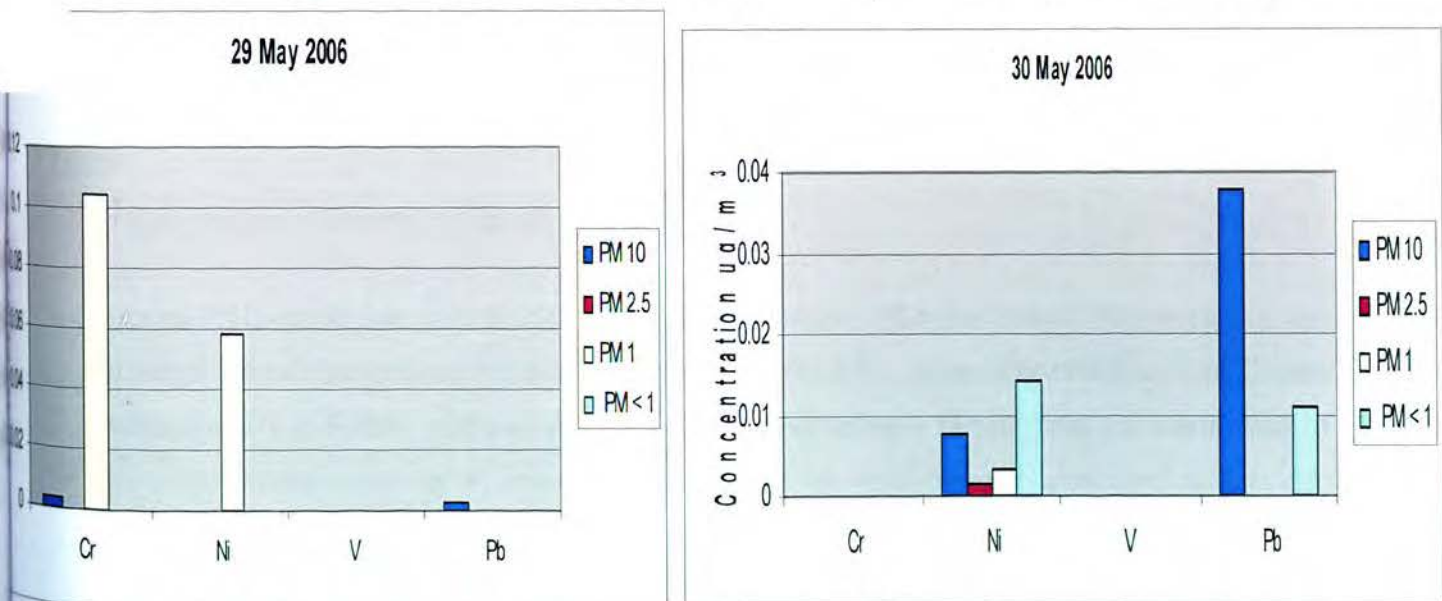


Figure 5.10 (a): Elemental Composition for Monday

Figure 5.10 (b): Elemental Composition for Tuesday

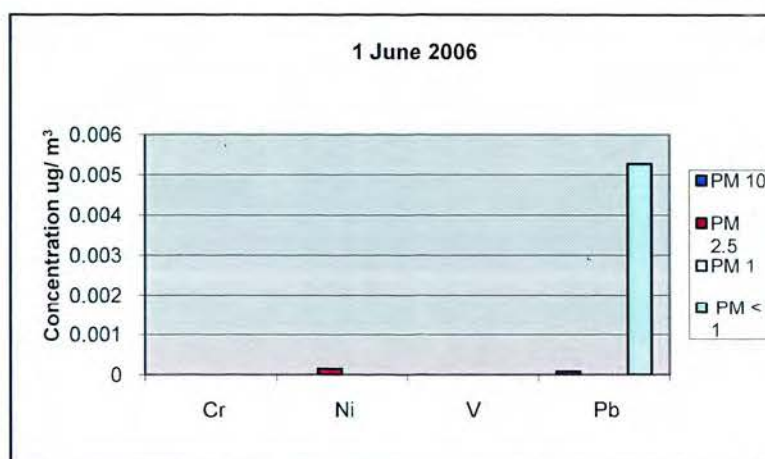
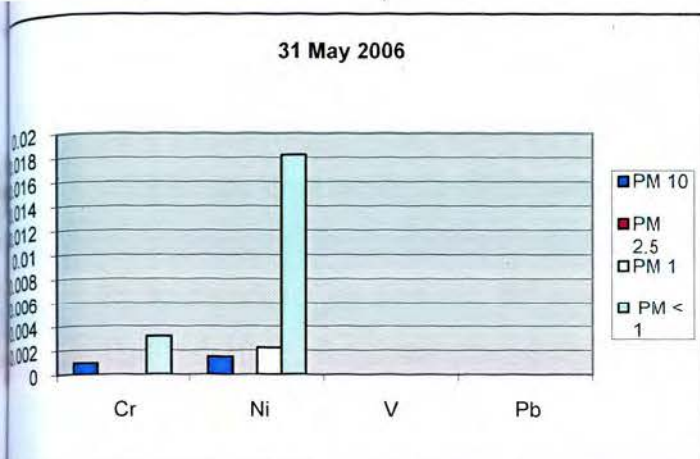


Figure 5.10 (c): Elemental Composition for Wednesday

Figure 5.10 (d): Elemental Composition for Thursday

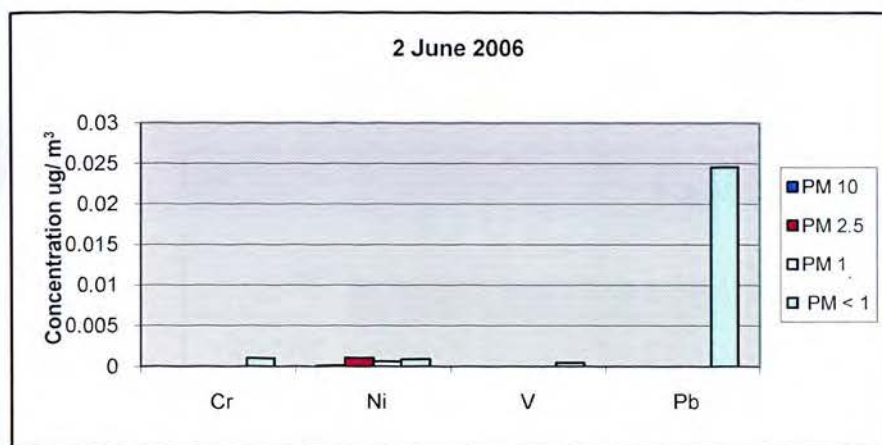


Figure 5.10 (e): Elemental Composition for Friday

Figure 5.10 (a) shows that the toxic metals of concern (Cr, Ni, V and Pb) were not present in large concentrations at the Klerksdorp sampling site. Low concentrations of Cr and Pb were present in PM₁₀, while Ni and Cr were found to have the highest concentration in PM₁. The study area is in the neighbourhood of gold-mining activities which do not necessarily contribute to emissions of V. The toxic elements of Cr and Ni were found in PM₁ may be due to the smelting of gold, whose mining produces Ni as one of the toxic by-product elements. The elements Ni and Cr which were found are in the fine particles that can penetrate deeper than coarse particles when inhaled.

The results shown in figures 5.10 (a) to (e) indicate that Ni was present on all days in varying amounts of concentrations. It was found mostly in fine particles (PM < 1) whose

concentration also tended to be high on those days. In view of the fact that gold mining does not give rise to emissions of Ni, the amount of Ni occurrence is linked with smelting and oil-fuelled plant emissions, this was also the observation in the study of (Held *et al.*, 1996) industrial region in Mpumalanga and Gauteng Regions.

In figures 5.10 (d) and (e), Pb has the highest concentration and in fine particles, while in figure 5.10 (b) it is present in both fine and coarse particles (PM 10). The main sources of lead are the particles from vehicular emissions and transport taking goods to the gold mine and people to work. Its presence in PM 10 is linked to high concentrations of PM 10 on the particular day.

5.5.2 Day–time Elemental Composition of PM in Klerksdorp on weekend

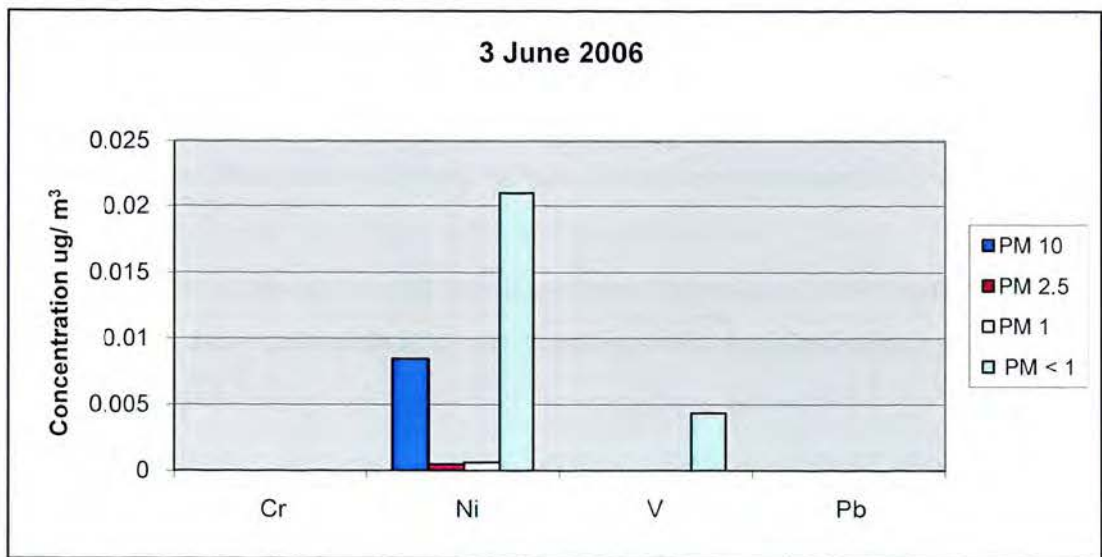


Figure 5.10 (f): Elemental Composition of Particulate Matter for 3 June 2006

The results shown in figure 5.10 (f) indicate the presence of Ni especially in fine particles PM < 1, but also in PM 10 and a little in PM 2.5 and PM 1. The fact that the wind speed was high on the day, and that its direction changed from south easterly in the morning to north easterly by the evening, taken in conjunction with figure 4.1 would point to the main road and a mine as likely sources. The absence of the other toxic elements except for small traces of V is consistent with the sources being linked to reduced human activity on

a weekend while the amount of Ni occurrence can be linked to smelting and oil-fuelled plant emissions (Held *et al.* 1996) in Mpumalanga.

5.6 COMPARISON BETWEEN THE RUSTENBURG AND KLERKSDORP ELEMENTAL COMPOSITIONS

The elements Cr, Ni, V and Pb were identified in almost all PM samples from the Rustenburg study site; whereas only a few samples in the Klerksdorp area contained these toxic elements. The elements also occurred in higher concentrations in Rustenburg than in Klerksdorp. This shows that the type of domestic and industrial activity around a source dictates the type of elements present in the particulate matter for the specific area. The fact that the Rustenburg concentrations for these elements were higher than the Klerksdorp levels still relates to the type of mining activity since the Rustenburg mines includes some that are open-pit while Klerksdorp is characterised by deep underground gold mines. The type of mining activities that take place in the Rustenburg area are for Chrome, Platinum and Vanadium mines, which create an impression that the source of toxic metals within the area are from activities associated with these mining operations. On the other hand, the type of mining activities that take place in the Khuma area are for Gold and as a result an impression is created that on this site the sources of toxic metals are from crustal sources.

5.7 COMPARISON OF TOXIC ELEMENTS (Pb, Cr, Ni, V) CONCENTRATIONS WITH INTERNATIONAL AIR QUALITY STANDARDS

The toxic element concentrations were compared with the international air quality standards. This type of comparison is useful in determining the health risks associated with these toxic elements. The mean concentration of the toxic metals obtained from each study site is compared to the available standards of limitation and shown in table 5.5.

Table 5.5 Summary of the concentration of the potential toxic trace metals in Rustenburg and Khuma areas.

Metal ($\mu\text{g.m}^{-3}$)	Rustenburg Site (Three hours)	Khuma Site	Standard or Limit
Cr - Range	0.02 – 5.2	0.001 – 0.12	1 $\mu\text{g.m}^{-3}$ – NOISH 1.5 $\mu\text{g.m}^{-3}$ – APCEL
Ni - Range	0.0012 – 0.04	0.003 – 0.08	No safe level - WHO
V - Range	0.003 – 0.06	0.003	1 $\mu\text{g.m}^{-3}$ – WHO
Pb - Range	0.004 – 0.3	0.002 – 0.04	0.5 $\mu\text{g.m}^{-3}$ – WHO



In Rustenburg the levels of Cr exceeded the limits when compared to the standards for National Institute for Occupational Safety and Health (NOISH) and Asia Pacific Centre for Environmental Law (APCEL), they even exceeded the standard for Cr, which is $2.5 \mu\text{g.m}^{-3}$. This metal is one of the harmful substances which should be managed well. Since the Ni ranged from 0.0012 to 0.04 and there is no safe level, every level of Ni that is released into the air is harmful. The concentrations on V and Pb were on an acceptable level since they did not exceed any standards.

In Khuma the presence of the toxic metals Cr, V and Pb did not exceed any standards. Since any level of inhaled Ni is not safe, this is the only metal that can be considered to pose a health hazard because of its relatively higher concentration when compared to Pb and V at this site.

CHAPTER 6

CONCLUSION

The occurrence of the toxic metals Chromium (Cr), Lead (Pb), Nickel (Ni) and Vanadium (V) in atmospheric aerosols of different sizes in the Rustenburg and Klerksdorp mining areas of the North West province was successfully determined in this study. The main objectives of this study were to determine the concentration levels of different sizes of particulate matter (PM 10, PM 2.5, PM 1 and PM <1) using a cascade impactor, and also to determine the presence of specific toxic metals in the different sizes of particulate matter; this was done using Particle Induced X-ray Emissions.

High concentrations for both PM 10 and PM 2.5 were found to occur in the winter period (May to June), and this has been attributed to the traffic density and combustion of fossil fuels for heating during winter. The fluctuations in the concentration levels can be attributed to prevailing meteorological conditions and local episodes. From figure 5.4 it is observed that the aggregate coarse particles PM10 + PM2.5 have higher concentrations during the week days than during the weekend days. The relatively high levels of PM<1 are attributed to re-suspension of particulate.

The PM concentrations were found to be higher in the Rustenburg study site than in the Klerksdorp site. The daytime PM levels were high ranging between 90 $\mu\text{g}/\text{m}^3$ and 0.5 $\mu\text{g}/\text{m}^3$ for Rustenburg and between 58 $\mu\text{g}/\text{m}^3$ and 0.3 $\mu\text{g}/\text{m}^3$ for Klerksdorp. The night-time concentrations ranged between 0.04 $\mu\text{g}/\text{m}^3$ and 0.8 $\mu\text{g}/\text{m}^3$, and between 0.01 and 0.2 $\mu\text{g}/\text{m}^3$ for the Rustenburg and Klerksdorp study sites respectively. In the Rustenburg area the sources were mainly anthropogenic as shown by the positive correlation between human activities and concentration, (road transport and stationary combustion sources). For the two study sites, concentrations of fine particles (PM < 1) were highest.

Particle induced X-ray emissions analyses of samples collected has shown that several heavy metals were emitted into the atmosphere from industries and area-based sources,

and these metals are associated with particulate matter in air. The toxic metals were mostly determined on the finer particles, which penetrate much deeper into the lungs. All the four toxic metals identified were found to have higher concentrations in Rustenburg than in Klerksdorp.

Lead emission from motor vehicles and petroleum services were found in large amounts and while lead is a critical air pollutant, it did not exceed the South African Standards. The reason could be that most of the cars use unleaded petrol, but trucks still use diesel containing a fair amount of lead. Chromium was abundant in almost all PM sizes while vanadium had the lowest concentrations. All the four toxic metals (Cr, Ni, V and Pb) were identified in the fine particles ($PM < 1$) for the Rustenburg area. This an important finding in view of their negative health effects because of their deeper penetration into the human body. This also implies that more people living around Rustenburg area are at risk of respiratory diseases due to high levels of ambient concentration of heavy metals measured in particulate matter. The results obtained on one weekday showed that Cr exceeded the limits of $1 \mu\text{g.m}^{-3}$ for NOISH and also the limit of $1.5 \mu\text{g.m}^{-3}$ for APCEL. Pb did not exceed the WHO standards of $0.5 \mu\text{g.m}^{-3}$, neither did V exceed the levels of $1 \mu\text{g.m}^{-3}$ set by WHO on that same day. The results obtained on another day also showed that Cr exceeded the limits of $1 \mu\text{g.m}^{-3}$ for NOISH but did not exceed $1.5 \mu\text{g.m}^{-3}$ for APCEL. Pb did not exceed the WHO standard of $0.5 \mu\text{g.m}^{-3}$ nevertheless lead concentrations generally were very high at $0.3 \mu\text{g.m}^{-3}$. The Cr weekend night concentration was found to be high when compared to the concentration during weekdays and this was attributed to a different mode of operation as a likely cause. It was further shown that the type of domestic and industrial activity around a pollution source dictates the type of elements present in the particulate matter for the specific area.

Particle induced X-ray emission proved to be effective in the determination of the elemental composition of atmospheric aerosols. This technique was sensitive, fast, and accurate since it could measure several metals simultaneously. The Dekati PM10 Cascade Impactor was also efficient in the sampling of particulate matter.

There is a need for more prolonged, continuous studies so as to establish trends and seasonal variations in particulate matter and the toxic metals. This study could not cover all the seasonal variations, which will be recommended in order to compare the difference in the seasons.

RECOMMENDATIONS

The recommendations for this study are as follows:

1. The sampling of particulate matter should be done for 24hr periods in order to enable comparison with South African standards and other international standards.
2. Measurements of particulate matter concentration need to be done in all seasons in-order to compare seasonal patterns.
3. The fact that concentrations of Cr have been found to be high in Rustenburg is a matter of concern since there are ferrochrome and platinum mines that use chrome as a bi-product in this area. The Rustenburg municipality should consider putting limits on Cr emissions from the mines in Rustenburg.
4. It is suggested that there should also be standards set for PM 2,5 in South Africa because they penetrate more than PM 10; the municipality can assist the national department by using results found in these areas.
5. Trucks must be monitored using vehicular equipment in-order to reduce emissions of Pb for both Rustenburg and Klerksdorp.
6. The municipality must be considering putting strict limits for PM 10 in the Rustenburg area since it is having a lot of activities in the area.
7. Since Ni is very toxic no matter how small the concentration may be, it is suggested that Klerksdorp should consider putting limits on Ni concentrations.

REFERENCES

AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY (ATSDR), Toxicological profiles, Cerla is the Comprehensive Environmental Response, Compensation and Liability, CHROMIUM, 2000.

AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY (ATSDR), Toxicological profiles, Cerla is the Comprehensive Environmental Response, Compensation and Liability, NICKEL, 1998.

AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY (ATSDR), Toxicological profiles, Cerla is the Comprehensive Environmental Response, Compensation and Liability, VANADIUM, 1993.

AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY (ATSDR), Toxicological profiles, Cerla is the Comprehensive Environmental Response, Compensation and Liability, LEAD, 1999.

ANCA BANCUTA, CLAUDIA STIHI, I.V., POPESCU, T., BADICA, Gh.V. CIMPOCA., Elemental analysis of aerosols using PIXE method Valahia University of Targoviste, Physics Dept., Romania National Institute for Physics and Nuclear Engineering-Horia Hulubei, Magurele, *J. Phys.: Conf. Ser.* **41**, 2006.

AZIN, F., Raie, R.M., and Mahmoudi, M.M., Correlation between the Levels of Certain Carcinogenic and Anticarcinogenic Trace Elements and Esophageal Cancer in Northern Iran. *Ecotoxicology and Environmental Safety* vol.39, 179 – 184, 1996.

BULLOCK, S., Sustainable Development Report. *Anglo Platinum Limited*, Johannesburg, 2006.

CANCIO, J.L., Castellano A.V., Hernández M.C., Bethencourt R.G and Ortega E.M., Metallic Species in Atmospheric Particulate Matter in Las Palmas de Gran Canaria. *J. Hazard. Mater.* 160: 521–528, 2008.

CHONG, N., Sivaramakrishna K., Wells, M., Jones, K., Characterization of Inhalable particulate matter in ambient air by Scanning Electron Microscopy and Energy-Dispersive X-ray Analysis. *Electron Journal of Environmental, Agriculture and Food Chemistry*, 1(3), pp.145- 166, 2002.

CLARKE, A.G., Azadi-Boogar, G.A., Andrews, G.E., Particle size and chemical composition of urban aerosols, *The Science of the Total Environment*, 235, 15-24, 1999.

DOCKERY, D.W., and Pope, C.A., Acute Respiratory Effects of Particulate Air Pollution. *Aun. Rev. Publ. Health* 15: 107–132, 1994.

ELEFTHERIADIS K and Colbeck I., "Coarse atmospheric aerosol: Size distributions of trace elements" *Atmos. Environment* Vol 35, pp 5321-5330, 2001.

EPA., Reference Method for the Determination of particulate matter as PM₁₀ in the Atmosphere. Federal Register, 62, no 138, Appendix M to part 50, 1997.

EPA., National Ambient Air Quality Standards for Particulate Matter. Federal Register, 62, no 138, 1997.

ESPINOSA, A.J.F., Rodríguez M.T., Barragán de la Rosa F.J and Jiménez Sánchez J.C., Size Distribution of Metals in Urban Aerosols in Seville (Spain). *Atmos. Environ.* 35: 2595–2601, 2001.

FORMENTI, P., Piketh, S.J., Annegarn, H.J., Time resolved aerosols monitoring in the urban centre of Soweto, 2004.

HELD, G., Gore, B.J., Surridge, A.D., Tosen, G.R., Turner, C.R., Walmsley, R.D (eds), Air pollution and its impacts on the South African Highveld, Environmental Science Association, Cleveland, 1996.

HINDS, W.C., Aerosols Technology: Properties, behavior, and measurement of airborne particles, 2nd edition, New York: John Wiley & Sons, 1998.

HINDS, W.C., Basis for particle size-selective sampling for wood dust. *Appl. Ind. Hyg*,3:67-72, Aerosol Technology. New York: John Wiley & Sons, 1999.

HOPPEL, W.A, Fitzgerald, J. W., Frick, G. M., and Larson, R. E., Aerosol size distributions and optical properties found in the marine boundary layer over the Atlantic ocean, *J. Geophys. Res.* 95-100, 1990.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC), Intergovernmental Panel on Climate Change, Cambridge Univ. Press, Cambridge, 1996.

KGABI, N. A., Pienaar, J.J., and Kulmala, M., Source of atmospheric pollutants in the North West Province of South Africa: a case of Rustenburg municipality, 2006.

LEE, S.W., Fuel Sulfur Effects on Particulate Emissions from Fuel Oil Combustion Systems Under Accelerated Laboratory Conditions, REPORT CETC 02-09(CF), 2002.

LEILI, M., Naddafi, K., Nabizadeh, R., and Yunesian, M., The Study of TSP and PM 10 Concentration and Their Heavy Metal Content in Central Area of Tehran, Iran. *Air Qual. Atmos. Health* 1: 159–166. Mar T.F, Larson T.V, Stier R.A, Claiborn, 2008.

MAENHAUT, W., Schwarz, J., Cafmeyer, J., Harold, J. A., Study of elemental mass size distributions at Skukuza, South Africa, during the SAFARI 2000 dry season campaign, 2002.

MIRANDA, J., Studies of atmospheric aerosols in large urban areas using PIXE: An overview, *Nuclear Instruments and methods in Physics, Research section B v 109*, 439-444, 1994.

NATIONAL PUBLIC HEALTH INSTITUTE DEPARTMENT OF ENVIRONMENTAL HEALTH, Characteristics and sources of fine particulate matters in urban air, University of Kuopio Press, 2005.

RESANE, T.T.V., Total hexavalent chromium in air sample, Thesis, MSc University of Witwatersrand, 2004.

ROBERTS, J., Sources, physico-chemical characteristic and climate forcing of atmospheric aerosols, *J Geophys. Res.* 2461-2478, 2001.

ROULET, C.A., Furbringer, J., Creton, P. The influence of the results of multizone air flow simulations with COMIS. *Energy and Buildings* 30, 73-86, 1999.

SATEESH, S.K., Aerosols and Climate. *Resonance*, 48-59, 1998.

SEINFELD, J.H., AND PANDIS, S.M., Atmospheric Chemistry and Physics, from air pollution to climate change. New York: John Wiley & Sons, 1998.

SHAH, M.H., Shaheen, N., and Jaffar, M., Characterization, Source Identification and Apportionment of Selected Metals in TSP in an Urban Atmosphere. *Environ. Monit. Assess.* 114: 573-587, (2006).

SIOUTAS, C., A pilot study to characterize fine particles in the environment of an automotive machining facility. *Appl. Occup. Environ. Hyg.* 14:246-254, 2001.

STATE OF THE AIR REPORT IN SOUTH AFRICA, A report on the state of air in South Africa. *Department of Environmental Affairs*, ISBN 978-0-621-38724-7 Pretoria, South Africa, 2005.

STATE OF THE ENVIRONMENTAL REPORT OVERVIEW NORTHWEST PROVINCE, *Department of Environmental Affairs and Tourism*, Republic of South Africa, 2002.

TABACNIKS, M.H., Orsini, C.Q., and Maenhau, W., *Nucl. Instr. and Meth. B* 75 262, 1993.

WALTER, J., *Size Distribution Characteristics of Aerosols Particle Science*, Walnut Creek, CA (1999, 2001).

WORLD RESOURCE INSTITUTE, *Urban Air: Health effects of particulate, sulphur dioxide, and ozone*. Geneva, 1999.

WORLD HEALTH ORGANIZATION, *Particulate Matter (PM₁₀ and PM_{2.5})*, How does particulate matter (PM) affect human health, 2003, 2 May 2006.

WINCHESTER W and Bi M.T., *Atm. Environ.* 18 (1984) 1399.

YIN, S.L., Pingsheng, H., Zhaohui, Z., Ming, Y., Shaojin, Y.Y., Qinfang, Q., and C. Bingru, *Int. J. PIXE* 2 593.G'91, 1992.

ZHANG, R.J., Xu, Y.F., and Han, Z.W., *Inorganic chemical composition and source signature of PM_{2.5} in Beijing during ACE-Asia period*, *Chinese Science Bulletin*, 48(10), 1002-1005, 2003.

Appendix A

Rustenburg data

End date	start time	end time	Collection time	Collect ed time	Foil / filter number	PM stage 10, 2.5, 1, backup filter	mass start	Mass end	collected mass	Gasometer start	Gasometer end	total volume	mass concent ration
19/06	19/06	9:00	12:00	3	247	10	5.8	6	0.201	2903,6	2909,4	5.8	0.6931
					292	2,5	5.96	6.2	0.237				0.8172
					271	1	5.73	6	0.271				0.9345
					5	Backup	142	149	7.182				24.766
19/06	19/06	12:00	15:00	3	280	10	5.61	6	0.39	2909,4	2914,8	5.4	1.4444
					257	2,5	5.91	6.7	0.788				2.9185
					267	1	5.68	6.8	1.119				4.1444
					4	Backup	146	147	1.012				3.7481
19/06	19/06	15:00	18:00	3	289	10	5.83	6.8	0.968	2914,8	2920,4	5.6	3.4571
					281	2,5	5.68	6.8	1.125				4.0179
					265	1	5.76	6.7	0.937				3.3464
					3	Backup	146	147	0.991				3.5393
20/06	20/06	6:00	9:00	3	278	10	5.74	6.7	0.96	2920,4	2924,4	4	4.8
					272	2,5	5.77	6	0.227				1.135
					270	1	5.78	6.7	0.917				4.585
					2	Backup	147	148	1.118				5.59
20/06	20/06	9:00	12:00	3	299	10	5.74	6.8	1.059	2924,4	2930,0	5.6	3.7821
					300	2,5	5.71	6.7	0.99				3.5357
					248	1	5.7	6.6	0.897				1
					1	Backup	145	146	1.108				3.9571
20/06	20/06	12:00	15:00	3	266	10	5.85	6.2	0.353	2930,0	2935,8	5.8	1.2172
					279	2,5	5.8	6.8	1.001				3.4517
					282	1	5.7	6.8	1.103				3.8034
					18	Backup	141	142	0.966				3.331
20/06	20/06	15:00	18:00	3	256	10	5.66	6.8	1.139	2935,8	2941,2	5.4	4.2185
					285	2,5	5.67	6.8	1.129				4.1815
					274	1	5.72	6.8	1.076				3.9852
					17	Backup	143	144	0.944				3.4963
20/06	21/06	18:00	6:00	12	288	10	5.75	6.2	0.452	2941,2	2965,4	24.2	0.0934
					283	2,5	5.65	6.7	1.05				0.2169
					269	1	5.77	6.8	1.026				0.212
					16	Backup	141	143	1.884				0.3893
21/06	21/06	6:00	9:00	3	293	10	5.72	6.8	1.084	2965,4	2969,8	4.4	4.9273
					275	2,5	5.89	6.2	0.309				1.4045
					277	1	5.64	6.6	0.96				4.3636

					15	Backup	145	146	1.12				5.0909
21/06	21/06	12:00	15:00	3	253	10	5.66	6.7	1.041	2969,8	2975,5	5.7	3.6526
					254	2,5	5.79	6.8	1.009				3.5404
					228	1	5.8	6.8	0.998				3.5018
					14	Backup	144	145	0.953				3.3439
21/06	21/06	15:00	18:00	3	239	10	5.61			2975,5	2982,0	6.5	
					224	2,5	5.79	6.7	0.91				2.8
					232	1	5.66	6.8	1.142				3.5138
					13	Backup	140	141	0.961				
21/06	22/06	18:00	6:00	12	372	10	5.77	6.7	0.935	2982,0	3004,7	22.7	0.2059
					252	2,5	5.68	6.8	1.125				0.2478
					377	1	5.76	6.2	0.442				0.0974
					12	Backup	140	144	3.917				0.8628
22/06	22/06	6:00	9:00	3	236	10	5.79	6.8	1.012	3004,7	3010,9	6.2	3.2645
					371	2,5	5.76	6	0.243				0.7839
					227	1	5.82	6	0.185				0.5968
					11	Backup	141	142	0.971				3.1323
22/06	22/06	9:00	12:00	3	245	10	5.83	6.7	0.873	3010,9	3015,2	4.3	4.0605
					374	2,5	5.64	6.6	0.964				4.4837
					243	1	5.76	6.8	1.044				4.8558
					30	Backup	142	143	0.906				4.214
22/06	22/06	12:00	15:00	3	244	10	5.94	6.4	0.463	3015,2	3020,6	5.4	1.7148
					375	2,5	5.72	6.8	1.08				4
					235	1	5.83	6.8	0.969				3.5889
					29	Backup	143	144	0.946				3.5037
22/06	22/06	15:00	18:00	3	225	10	5.72	6.8	1.077	3020,6	3026,1	5.5	3.9164
					237	2,5	5.76	6.6	0.838				3.0473
					338	1	5.68	6	0.317				1.1527
					28	Backup	144	145	0.978				3.5564
22/06	23/06	18:00	6:00	12	229	10	5.77	6.2	0.426	3026,1	3048,1	22	0.0968
					226	2,5	5.86	6.8	0.938				0.2132
					310	1	5.79	6	0.207				0.047
					27	Backup	142	143	1.085				0.2466
23/06	23/06	6:00	9:00	3	373	10	5.78	6.8	1.025	3048,1	3053,4	5.3	3.8679
					337	2,5	5.74	6.7	0.963				3.634
					378	1	5.8	6.7	0.897				3.3849
					26	Backup	147	148	1.009				3.8075
23/06	23/06	9:00	12:00	3	340	10	5.71	6.6	0.886	3053,4	3059,0	5.6	3.1643
					319	2,5	5.67	6	0.33				1.1786
					329	1	5.84	6.2	0.364				1.3
					126	Backup	144	145	0.93				3.3214
23/06	23/06	12:00	15:00	3	376	10	5.81	6.2	0.389	3059,0	3064,3	5.3	
					240	2,5	5.79	6	0.209				0.7887
					238	1	5.78	6.8	1.019				3.8453

					127	Backup	144	145	0.937				3.5358
23/06	23/06	15:00	18:00	3	308	10	5.83	6.2	0.366	3064,3	3070,4	6.1	1.2
					246	2,5	5.78	6	0.225				0.7377
					230	1	5.97	6.7	0.726				2.3803
					128	Backup	144	145	0.967				3.1705
23/06	24/06	18:00	6:00	12	242	10	5.67	6.8	1.132	3070,4	3093,1	22.7	0.2493
					316	2,5	5.83	6.7	0.872				0.1921
					260	1	5.76	6	0.244				0.0537
					129	Backup	142	144	1.75				0.3855
24/06	24/06	6:00	9:00	3	317	10	5.83	6.7	0.87	3093,1	3098,6	5.5	3.1636
					336	2,5	5.69	6.8	1.115				4.0545
					307	1	5.77	6.2	0.434				1.5782
					130	Backup	143	144	1.15				4.1818
24/06	24/06	9:00	12:00	3	320	10	5.74	6.8	1.056	3098,6	3104,2	5.6	3.7714
					241	2,5	5.76	6.8	1.045				3.7321
					339	1	5.78	6.7	0.924				3.3
					111	Backup	146	147	0.977				3.4893
24/06	24/06	12:00	15:00	3	309	10	5.77	6.8	1.034	3104,2	3109,6	5.4	3.8296
					305	2,5	5.77	6.2	0.433				1.6037
					327	1	5.78	6	0.223				0.8259
					112	Backup	144	145	0.951				3.5222
24/06	24/06	15:00	18:00	3	255	10	5.81	6	0.187	3109,6	3115,2	5.6	0.6679
					318	2,5	5.79	6	0.211				0.7536
					329	1	5.85	6.2	0.36				1.2857
					113	Backup	145	146	0.987				3.525
24/06	25/06	18:00	6:00	12	330	10	5.82	6.7	0.879	3115,2	3139,4	24.2	0.1816
					231	2,5	5.8	6	0.198				0.0409
					304	1	5.74	6.8	1.057				0.2184
					114	Backup	145	146	1.549				0.32
25/06	25/06	6:00	9:00	3	326	10	5.75	6.2	0.446	3139,4	3144,0	4.6	1.9391
					315	2,5	5.88	6.8	0.916				3.9826
					306	1	5.93	6.2	0.266				1.1565
					115	Backup	144	145	0.963				4.187
25/06	25/06	9:00	12:00		478	10	5.8	6.7	0.898	3144,0	3149,2	5.2	3.4538
					482	2,5	5.91	6	0.088				0.3385
					498	1	5.71	6.8	1.089				4.1885
					116	Backup	146	147	1.001				3.85
25/06	25/06	12:00	15:00		554	10	5.69	6.6	0.91	3149,2	3154,9	5.7	3.193
					530	2,5	5.8	6.7	0.902				3.1649
					511	1	5.8	6.8	0.998				3.5018
					117	Backup	146	147	0.929				3.2596
25/06	25/06	15:00	18:00		521	10	5.77	6.7	0.927	3154,9	3160,4	5.5	3.3709
					451	2,5	5.68	6.8	1.124				4.0873
					553	1	5.74	6.8	1.056				

					118	Backup	146	147	0.943				3.4291
25/06	26/06	18:00	6:00	12	531	10	5.74	6.6	0.859	3160,4	3182,5	22.1	0.1943
					512	2,5	5.84	6.4	0.565				0.1278
					500	1	5.7	6.8	1.099				0.2486
					119	Backup	146	148	1.752				0.3964
26/06	26/06	6:00	9:00		439	10	5.68	6.7	1.025	3182,5	3188,0	5.5	
					533	2,5	5.75	6.8	1.048				
					467	1	5.91	6	0.088				
					120	Backup	145	146	1.012				
26/06	26/06	9:00	12:00		419	10	5.64	6.8	1.161	3188,0	3193,9	5.9	
					509	2,5	5.79	6.3	0.515				
					532	1	5.67	6.7	1.031				
					101	Backup	144	146	1.944				
26/06	26/06	12:00	15:00		513	10	5.85	6.8	0.946	3193,9	3199,5	5.6	
					429	2,5	5.76	6.7	0.94				
					510	1	5.75	6.7	0.948				
					102	Backup	144	145	0.948				
26/06	26/06	15:00	18:00		432	10	5.76	6.8	1.037	3199,5	3205,3	5.8	
					445	2,5	5.75	6.8	1.048				
					442	1	5.78	6.2	0.424				
					103	Backup	145	145	0.4				
26/06	27/06	18:00	6:00	12	503	10	5.78	6.7	0.921	3205,3	3227,7	22.4	
					544	2,5	5.67	6	0.331				
					452	1	5.66	6	0.344				
					104	Backup	145	146	1.257				
27/06	27/06	6:00	9:00		421	10	5.66	6.7	1.036	3227,7	3232,9	5.2	
					435	2,5	5.66	6.8	1.141				
					433	1	5.72	6.2	0.485				
					105	Backup	147	148	0.961				
27/06	27/06	9:00	12:00		453	10	5.75	6	0.253	3232,9	3238,5	5.6	
					529	2,5	5.81	6.8	0.989				
					425	1	5.79	6.7	0.91				
					106	Backup	147	148	0.946				
27/06	27/06	12:00	15:00		501	10	5.79	6	0.214	3238,5	3244,2	5.7	
					449	2,5	5.7	6.6	0.896				
					450	1	5.71	6.6	0.889				
					107	Backup	145	146	0.929				
27/06	27/06	15:00	18:00		443	10	5.66	6.8	1.136	3244,2	3249,5	5.3	
					440	2,5	5.61	6.6	0.989				
					455	1	5.66	6	0.338				
					108	Backup	143	144	0.925				
27/06	28/06	18:00	6:00	12	543	10	5.74	6.8	1.063	3249,5	3272,0	22.5	
					434	2,5	5.68						
					420	1	5.66	6.8	1.138				

					109	Backup	145	147	1.411				
28/06	28/06	6:00	9:00		424	10	5.55			3272,0	3277,4	5.4	
					430	2,5	5.63						
					456	1	5.73						
					110	Backup	145						
28/06	28/06	9:00	12:00		441	10	5.7			3277,4	3282,0	4.8	
					520	2,5	5.75						
					454	1	5.7						
					141	Backup	146						
28/06	28/06	12:00	15:00		423	10	5.61			3282,0	3289,0	7	
					444	2,5	5.69						
					502	1	5.65						
					142	Backup	145						
28/06	28/06	15:00	18:00		523	10	5.64			3289,0	3294,2	5.2	
					422	2,5	5.72						
					431	1	5.69						
					143	Backup	146						

Klerksdorp (Khuma) Data

Start date	End date	start time	end time	Foil / filter number	PM stage 10, 2.5, 1, backup filter	mass start	Mass end	collected mass	Gasometer start	Gasometer end	total volume	mass concentration
29/05	29/05	9:00	12:00	207	10	5.698	6	0.302	2624,1	2628,9	4.8	1.2583333
				185	2,5	5.727	5.9	0.173				0.7208333
				173	1	5.634	6.6	0.966				4.025
				39	Backup	142.77	143.66	0.888				3.7
29/05	29/05	12:00	15:00	184	10	5.682	5.8	0.118	2628,9	2634,6	5.7	0.4140351
				201	2,5	5.771	6	0.229				0.8035088
				174	1	5.721	6	0.279				0.9789474
				37	Backup	141.84	142.74	0.9				3.1578947
29/05	29/05	15:00	8:00	211	10	5.735	6	0.265	2634,6	2668,7	34.1	0.0259042
				198	2,5	5.792	6.3	0.507				0.0495601
				213	1	5.837	6	0.163				0.0159335
				25	Backup	142.35	144.29	1.942				0.1898338

30/05	30/05	9:00	12:00	200	10	5.721	6.6	0.879	2668,7	2674,6	5.9	2.979661
				177	2,5	5.647	5.9	0.253				0.8576271
				196	1	5.753	5.8	0.047				0.159322
				34	Backup	144.5	145.45	0.95				3.220339
30/05	30/05	12:00	15:00	176	10	5.747	6.8	1.053	2674,6	2679,9	5.3	3.9735849
				212	2,5	5.772	5.8	0.028				0.1056604
				218	1	5.649	6.1	0.451				1.7018868
				35	Backup	143.87	144.86	0.988				3.7283019
30/05	30/05	15:00	8:00	179	10	5.735	6.7	0.965	2679,9	2714,2	39.6	0.081229
				187	2,5	5.77	6.1	0.33				0.0277778
				220	1	5.73	6.7	0.97				0.0816498
				46	Backup	142.01	143.59	1.576				0.1326599
31/05	31/05	9:00	12:00	206	10	5.71	5.8	0.09	2714,2	2719,7	5.5	0.3272727
				222	2,5	5.798	6.7	0.902				3.28
				221	1	5.736	5.9	0.164				0.5963636
				47	Backup	140.92	141.88	0.963				3.5018182
31/05	31/05	12:00	15:00	178	10	5.702	6.6	0.898	2719,7	2725,3	5.6	3.2071429
				204	2,5	5.801	6.2	0.399				1.425
				215	1	5.73	6.8	1.07				3.8214286
				45	Backup	143.18	144.1	0.921				3.2892857
31/05	1/06	15:00	8:00	193	10	5.677	6.8	1.123	2725,3	2759,4	34.1	0.1097752
				203	2,5	5.739	6.7	0.961				0.0939
				210	1	5.753	6.3	0.547				0.0534702
				44	Backup	141.41	143.42	2.01				0.1964809
1/06	1/06	9:00	12:00	188	10	5.76	6	0.24	2759,4	2764,6	5.2	0.9230769
				219	2,5	5.686	5.9	0.214				0.8230769
				180	1	5.724	6.7	0.976				3.7538462
				50	Backup	143.24	144.17	0.932				3.5846154
1/06	1/06	12:00	15:00	197	10	5.812	6.1	0.288	2764,6	2770,2	5.6	1.0285714
				216	2,5	5.664	5.9	0.236				0.8428571
				195	1	5.813	6	0.187				0.6678571
				42	Backup	142.67	143.58	0.089				0.3178571
1/06	2/06	15:00	8:00	560	10	5.731	5.9	0.169	2770,2	2804,0	33.8	0.0166667
				276	2,5	5.628	6.2	0.572				0.0564103

				558	1	5.657	6	0.343				0.0338264
				20	Backup	143.74	144.62	0.881				0.0868836
2/06	2/06	9:00	12:00	286	10	5.7	5.9	0.2	2804,0	2809,6	5.6	0.7142857
				284	2,5	5.761	5.8	0.039				0.1392857
				559	1	5.71	6.8	1.09				3.8928571
				19	Backup	141.03	141.35	0.321				1.1464286
2/06	2/06	12:00	15:00	549	10	5.828	5.9	0.072	2809,6	2814,9	5.3	0.2716981
				258	2,5	5.753	5.9	0.147				0.525
				249	1	5.737	5.9	0.163				0.5821429
				43	Backup	140.44	142.09	1.647				5.8821429
2/06	3/06	15:00	8:00	295	10	5.658	5.8	0.142	2814,9	2848,6	33.7	0.0140455
				262	2,5	5.725	6.7	0.975				0.0964392
				264	1	5.742	6.3	0.558				0.0551929
				41	Backup	143.69	145.52	1.832				0.1812067
3/06	3/06	9:00	12:00	290	10	5.839	6	0.161	2848,6	2854,0	5.4	0.5962963
				251	2,5	5.713	5.9	0.187				0.6925926
				273	1	5.871	6.7	0.829				3.0703704
				10	Backup	142.88	143.86	0.976				3.6148148
3/06	3/06	12:00	15:00	250	10	5.659	6.8	1.141	2854,0	2859,4	5.4	4.2259259
				261	2,5	5.844	5.9	0.056				0.2074074
				294	1	5.703	5.8	0.097				0.3592593
				9	Backup	142.37	143.28	0.907				3.3592593
3/06	4/06	15:00	8:00	538	10	5.659	6.3	0.641	2859,4	2894,1	38.7	0.055211
				268	2,5	5.753	6.1	0.347				0.029888
				296	1	5.862	6.2	0.338				0.0291128
				7	Backup	146.46	148.21	1.747				0.1504737
4/06	4/06	9:00	12:00	291	10	5.713	6.8	1.087	2894,1	2898,7	4.6	4.726087
				263	2,5	5.729	6.6	0.871				3.7869565
				287	1	5.791	6.6	0.809				3.5173913
				8	Backup	139.89	140.79	0.904				3.9304348
4/06	4/06	12:00	15:00	298	10	5.785	6.1	0.315	2898,7	2903,6	4.9	1.2857143
				259	2,5	5.84	6.2	0.36				1.4693878
				297	1	5.848	5.9	0.052				0.2122449
				6	Backup	148.54	149.53	0.993				4.0530612

Appendix B

Rustenburg Meteorology data (a)

Station_Number	Station_Name	Date	Hour	Rain	Temp	Speed Height: 1,150 m	Dir	Hum	Press
0511399 X	RUSTENBURG	Lat:	25.65	Long:	27.23		CurOrder:	ELEC_TEMP	
0511399 X	RUSTENBURG	6/19/2006	1	0	4.8	0	0		896.3
0511399 X	RUSTENBURG	6/19/2006	2	0	4.9	1.5	226		896
0511399 X	RUSTENBURG	6/19/2006	3	0	4.6	0	0		895.9
0511399 X	RUSTENBURG	6/19/2006	4	0	4.7	1.5	227		895.6
0511399 X	RUSTENBURG	6/19/2006	5	0	4	0	0		895.7
0511399 X	RUSTENBURG	6/19/2006	6	0	3.5	0	0		896.6
0511399 X	RUSTENBURG	6/19/2006	7	0	3.3	1.3	226		897.2
0511399 X	RUSTENBURG	6/19/2006	8	0	6.6	1.2	222		897.5
0511399 X	RUSTENBURG	6/19/2006	9	0	12.5	0	0		898.1
0511399 X	RUSTENBURG	6/19/2006	10	0	14.7	0	0		898.1
0511399 X	RUSTENBURG	6/19/2006	11	0	15.7	1.7	39		897.7
0511399 X	RUSTENBURG	6/19/2006	12	0	18.2	1.7	35		896.7
0511399 X	RUSTENBURG	6/19/2006	13	0	19.1	1.6	16		895.5
0511399 X	RUSTENBURG	6/19/2006	14	0	21.2	1.5	26		894.5
0511399 X	RUSTENBURG	6/19/2006	15	0	21.3	2.4	176		894.3
0511399 X	RUSTENBURG	6/19/2006	16	0	20.6	2.4	183		894.3
0511399 X	RUSTENBURG	6/19/2006	17	0	18.6	2.4	170		894.7
0511399 X	RUSTENBURG	6/19/2006	18	0	14.6	1.1	191		895.1
0511399 X	RUSTENBURG	6/19/2006	19	0	11.9	1.2	225		895.6
0511399 X	RUSTENBURG	6/19/2006	20	0	11.4	0	0		896.2
0511399 X	RUSTENBURG	6/19/2006	21	0	9.2	1.2	238		896.5
0511399 X	RUSTENBURG	6/19/2006	22	0	6.9	0	0		896.8
0511399 X	RUSTENBURG	6/19/2006	23	0	8.1	0	0		897.1
0511399 X	RUSTENBURG	6/20/2006	0	0	6.5	0	0		896.8
0511399 X	RUSTENBURG	6/20/2006	1	0	5.5	0	0		897.1
0511399 X	RUSTENBURG	6/20/2006	2	0	5.6	1.8	229		896.7
0511399 X	RUSTENBURG	6/20/2006	3	0	4.7	1.6	228		896.9
0511399 X	RUSTENBURG	6/20/2006	4	0	3.9	1.6	231		897
0511399 X	RUSTENBURG	6/20/2006	5	0	3.3	1.2	244		897.1
0511399 X	RUSTENBURG	6/20/2006	6	0	2.9	1.6	233		897.3
0511399 X	RUSTENBURG	6/20/2006	7	0	3	1.5	234		897.6
0511399 X	RUSTENBURG	6/20/2006	8	0	6.2	1.8	229		897.7
0511399 X	RUSTENBURG	6/20/2006	9	0	12.5	0	0		898.1
0511399 X	RUSTENBURG	6/20/2006	10	0	15.7	0	0		898.6
0511399 X	RUSTENBURG	6/20/2006	11	0	16.4	1.2	59		898.3
0511399 X	RUSTENBURG	6/20/2006	12	0	17.5	1.2	33		897.4
0511399 X	RUSTENBURG	6/20/2006	13	0	18.7	1.5	39		896.1
0511399 X	RUSTENBURG	6/20/2006	14	0	19.1	1.6	58		895.3
0511399 X	RUSTENBURG	6/20/2006	15	0	19.7	1.4	64		894.8
0511399 X	RUSTENBURG	6/20/2006	16	0	19	1.6	49		894.4
0511399 X	RUSTENBURG	6/20/2006	17	0	17.4	0	0		894.5
0511399 X	RUSTENBURG	6/20/2006	18	0	12.2	0	0		894.9

0511399 X	RUSTENBURG	6/20/2006	19	0	10	1.6	228	895.3
0511399 X	RUSTENBURG	6/20/2006	20	0	9.1	1.9	226	895.6
0511399 X	RUSTENBURG	6/20/2006	21	0	8.9	1.9	231	895.6
0511399 X	RUSTENBURG	6/20/2006	22	0	7.7	1.3	234	895.5
0511399 X	RUSTENBURG	6/20/2006	23	0	6.4	0	0	895.5
0511399 X	RUSTENBURG	6/21/2006	0	0	5.1	0	0	895.3
0511399 X	RUSTENBURG	6/21/2006	1	0	5.5	1.3	240	894.9
0511399 X	RUSTENBURG	6/21/2006	2	0	3.3	0	0	894.9
0511399 X	RUSTENBURG	6/21/2006	3	0	3.8	1.3	227	894.7
0511399 X	RUSTENBURG	6/21/2006	4	0	4.2	1.8	231	894.5
0511399 X	RUSTENBURG	6/21/2006	5	0	3.7	1.7	228	894.1
0511399 X	RUSTENBURG	6/21/2006	6	0	4.1	2.3	228	894.2
0511399 X	RUSTENBURG	6/21/2006	7	0	4.3	1.9	227	894.5
0511399 X	RUSTENBURG	6/21/2006	8	0	7.3	1.8	228	894.8
0511399 X	RUSTENBURG	6/21/2006	9	0	11	0	0	895.2
0511399 X	RUSTENBURG	6/21/2006	10	0	15.1	0	0	895.2
0511399 X	RUSTENBURG	6/21/2006	11	0	17.4	0	0	894.3
0511399 X	RUSTENBURG	6/21/2006	12	0	18.7	1.3	35	893.4
0511399 X	RUSTENBURG	6/21/2006	13	0	20.1	1.3	21	892.1
0511399 X	RUSTENBURG	6/21/2006	14	0	21.4	1.2	7	891
0511399 X	RUSTENBURG	6/21/2006	15	0	21.2	1.4	351	890.3
0511399 X	RUSTENBURG	6/21/2006	16	0	21	1.9	302	889.9
0511399 X	RUSTENBURG	6/21/2006	17	0	18.9	1.9	319	890
0511399 X	RUSTENBURG	6/21/2006	18	0	15.2	0	0	890.3
0511399 X	RUSTENBURG	6/21/2006	19	0	11.1	0	0	890.7
0511399 X	RUSTENBURG	6/21/2006	20	0	9.3	0	0	890.9
0511399 X	RUSTENBURG	6/21/2006	21	0	14.6	1.5	256	891.2
0511399 X	RUSTENBURG	6/21/2006	22	0	13.8	2.6	252	891.3
0511399 X	RUSTENBURG	6/21/2006	23	0	8.4	1.4	222	891
0511399 X	RUSTENBURG	6/22/2006	0	0	4.9	0	0	890.9
0511399 X	RUSTENBURG	6/22/2006	1	0	3.5	0	0	890.8
0511399 X	RUSTENBURG	6/22/2006	2	0	2.9	0	0	890.6
0511399 X	RUSTENBURG	6/22/2006	3	0	2.7	1.3	233	890.2
0511399 X	RUSTENBURG	6/22/2006	4	0	2.9	1.1	233	890.2
0511399 X	RUSTENBURG	6/22/2006	5	0	2.2	0	0	889.9
0511399 X	RUSTENBURG	6/22/2006	6	0	1.9	0	0	890
0511399 X	RUSTENBURG	6/22/2006	7	0	3.1	0	0	890.4
0511399 X	RUSTENBURG	6/22/2006	8	0	7	0	0	890.5
0511399 X	RUSTENBURG	6/22/2006	9	0	12.8	0	0	890.7
0511399 X	RUSTENBURG	6/22/2006	10	0	18.1	2.7	224	890.7
0511399 X	RUSTENBURG	6/22/2006	11	0	19.6	2.4	199	890
0511399 X	RUSTENBURG	6/22/2006	12	0	20.6	3.1	224	889.6
0511399 X	RUSTENBURG	6/22/2006	13	0	20.7	3.3	240	888.5
0511399 X	RUSTENBURG	6/22/2006	14	0	21.3	3.6	240	887.9
0511399 X	RUSTENBURG	6/22/2006	15	0	20.9	3.7	240	887.9
0511399 X	RUSTENBURG	6/22/2006	16	0	19.8	3.7	238	888.1
0511399 X	RUSTENBURG	6/22/2006	17	0	18.3	2.5	254	888.1
0511399 X	RUSTENBURG	6/22/2006	18	0	13.4	0	0	888.8

0511399 X	RUSTENBURG	6/22/2006	19	0	12	0	0	889.4
0511399 X	RUSTENBURG	6/22/2006	20	0	13.7	2.1	202	890.2
0511399 X	RUSTENBURG	6/22/2006	21	0	12.3	3.7	205	890.7
0511399 X	RUSTENBURG	6/22/2006	22	0	11.4	4.4	208	890.8
0511399 X	RUSTENBURG	6/22/2006	23	0	10	3.9	201	891.4
0511399 X	RUSTENBURG	6/23/2006	0	0	9.3	1.9	63	891.8
0511399 X	RUSTENBURG	6/23/2006	1	0	8.4	3.6	159	891.5
0511399 X	RUSTENBURG	6/23/2006	2	0	7.7	1.4	180	891.2
0511399 X	RUSTENBURG	6/23/2006	3	0	6.9	1.1	11	891.5
0511399 X	RUSTENBURG	6/23/2006	4	0	5.6	0	0	892.1
0511399 X	RUSTENBURG	6/23/2006	5	0	5.4	0	0	892.5
0511399 X	RUSTENBURG	6/23/2006	6	0	3.9	1.5	159	892.9
0511399 X	RUSTENBURG	6/23/2006	7	0	3.1	1.6	226	893.4
0511399 X	RUSTENBURG	6/23/2006	8	0	6.1	1.3	231	894.4
0511399 X	RUSTENBURG	6/23/2006	9	0	11	0	0	895.2
0511399 X	RUSTENBURG	6/23/2006	10	0	12.3	1.3	91	895.6
0511399 X	RUSTENBURG	6/23/2006	11	0	13.9	1.2	68	895.4
0511399 X	RUSTENBURG	6/23/2006	12	0	15.1	1.5	56	894.8
0511399 X	RUSTENBURG	6/23/2006	13	0	16.4	0	0	893.9
0511399 X	RUSTENBURG	6/23/2006	14	0	17.3	1.4	118	893.3
0511399 X	RUSTENBURG	6/23/2006	15	0	17.3	1.1	326	893.1
0511399 X	RUSTENBURG	6/23/2006	16	0	16.8	1.1	50	893.1
0511399 X	RUSTENBURG	6/23/2006	17	0	15.5	0	0	893.2
0511399 X	RUSTENBURG	6/23/2006	18	0	10.4	0	0	893.7
0511399 X	RUSTENBURG	6/23/2006	19	0	8.1	1.7	227	894.7
0511399 X	RUSTENBURG	6/23/2006	20	0	7.3	1.9	226	895.1
0511399 X	RUSTENBURG	6/23/2006	21	0	7.1	2	224	895.6
0511399 X	RUSTENBURG	6/23/2006	22	0	6.2	1.8	229	895.7
0511399 X	RUSTENBURG	6/23/2006	23	0	5.1	1.6	229	895.7
0511399 X	RUSTENBURG	6/24/2006	0	0	3.9	0	0	895.5
0511399 X	RUSTENBURG	6/24/2006	1	0	2.3	0	0	895.3
0511399 X	RUSTENBURG	6/24/2006	2	0	1.7	0	0	895.2
0511399 X	RUSTENBURG	6/24/2006	3	0	1.8	0	0	895.1
0511399 X	RUSTENBURG	6/24/2006	4	0	0.9	0	0	895.2
0511399 X	RUSTENBURG	6/24/2006	5	0	0.1	0	0	895.2
0511399 X	RUSTENBURG	6/24/2006	6	0	0	0	0	895.8
0511399 X	RUSTENBURG	6/24/2006	7	0	-0.1	0	0	896.1
0511399 X	RUSTENBURG	6/24/2006	8	0	3.8	0	0	896.6
0511399 X	RUSTENBURG	6/24/2006	9	0	10.3	0	0	897
0511399 X	RUSTENBURG	6/24/2006	10	0	13.4	1.3	29	897.3
0511399 X	RUSTENBURG	6/24/2006	11	0	15.6	1.5	31	896.9
0511399 X	RUSTENBURG	6/24/2006	12	0	16.5	1.2	18	896.2
0511399 X	RUSTENBURG	6/24/2006	13	0	18	1.4	43	895
0511399 X	RUSTENBURG	6/24/2006	14	0	18.3	1.7	28	894.1
0511399 X	RUSTENBURG	6/24/2006	15	0	19.1	1.5	12	893.7
0511399 X	RUSTENBURG	6/24/2006	16	0	19.1	1.3	360	893.2
0511399 X	RUSTENBURG	6/24/2006	17	0	17	1.5	360	893.2
0511399 X	RUSTENBURG	6/24/2006	18	0	11.8	0	0	893.5

0511399 X	RUSTENBURG	6/24/2006	19	0	8.7	0	0	894
0511399 X	RUSTENBURG	6/24/2006	20	0	6.7	0	0	894.6
0511399 X	RUSTENBURG	6/24/2006	21	0	5.5	0	0	894.8
0511399 X	RUSTENBURG	6/24/2006	22	0	5.4	0	0	895
0511399 X	RUSTENBURG	6/24/2006	23	0	4.5	0	0	895.1
0511399 X	RUSTENBURG	6/25/2006	0	0	2.7	0	0	895.1
0511399 X	RUSTENBURG	6/25/2006	1	0	1.7	0	0	894.9
0511399 X	RUSTENBURG	6/25/2006	2	0	1.7	0	0	894.6
0511399 X	RUSTENBURG	6/25/2006	3	0	1.1	0	0	894.4
0511399 X	RUSTENBURG	6/25/2006	4	0	0.6	0	0	894.3
0511399 X	RUSTENBURG	6/25/2006	5	0	-0.1	0	0	894.1
0511399 X	RUSTENBURG	6/25/2006	6	0	0.4	0	0	894.4
0511399 X	RUSTENBURG	6/25/2006	7	0	-0.3	0	0	894.9
0511399 X	RUSTENBURG	6/25/2006	8	0	4.7	0	0	895.4
0511399 X	RUSTENBURG	6/25/2006	9	0	12.8	0	0	895.6
0511399 X	RUSTENBURG	6/25/2006	10	0	15.6	0	0	895.9
0511399 X	RUSTENBURG	6/25/2006	11	0	18.1	1.7	152	895.4
0511399 X	RUSTENBURG	6/25/2006	12	0	18.9	2.2	162	894.6
0511399 X	RUSTENBURG	6/25/2006	13	0	20.2	1.9	160	893.6
0511399 X	RUSTENBURG	6/25/2006	14	0	21.1	1.2	131	892.7
0511399 X	RUSTENBURG	6/25/2006	15	0	21.4	1.5	154	892.5
0511399 X	RUSTENBURG	6/25/2006	16	0	20.6	2	174	892.6
0511399 X	RUSTENBURG	6/25/2006	17	0	18.6	0	0	892.9
0511399 X	RUSTENBURG	6/25/2006	18	0	11.4	0	0	893.4
0511399 X	RUSTENBURG	6/25/2006	19	0	9.3	1.2	250	894.1
0511399 X	RUSTENBURG	6/25/2006	20	0	6.3	0	0	894.9
0511399 X	RUSTENBURG	6/25/2006	21	0	5.2	0	0	895.2
0511399 X	RUSTENBURG	6/25/2006	22	0	3.4	1.3	234	895.6
0511399 X	RUSTENBURG	6/25/2006	23	0	1.9	0	0	895.8
Limitation								

Klerksdorp data Meteorology (b)

Station_Number	Station_Name	Date	Hour	Rain	Temp	Speed Height: 1,322 m	Dir CurOrder:	Press
0436204 1	KLERKSDORP	Lat:	-26.9	Long:	26.62			
0436204 1	KLERKSDORP	5/29/2006	1	0	5.1	1.3	324	876.8
0436204 1	KLERKSDORP	5/29/2006	2	0	6	2.1	319	876.8
0436204 1	KLERKSDORP	5/29/2006	3	0	3.6	0	0	876.5
0436204 1	KLERKSDORP	5/29/2006	4	0	3	0	0	876.9
0436204 1	KLERKSDORP	5/29/2006	5	0	2	0	0	876.8
0436204 1	KLERKSDORP	5/29/2006	6	0	2.1	1.4	329	876.9
0436204 1	KLERKSDORP	5/29/2006	7	0	1.6	1.4	334	877.5
0436204 1	KLERKSDORP	5/29/2006	8	0	4.3	0	0	878.6
0436204 1	KLERKSDORP	5/29/2006	9	0	9.8	0	0	879.4

0436204 1	KLERKSDORP	5/29/2006	10	0	15.1	1.9	81	879.4
0436204 1	KLERKSDORP	5/29/2006	11	0	17.9	3.4	82	878.7
0436204 1	KLERKSDORP	5/29/2006	12	0	19.9	2.5	68	878.2
0436204 1	KLERKSDORP	5/29/2006	13	0	21.3	2.2	67	877.5
0436204 1	KLERKSDORP	5/29/2006	14	0	22.6	2	71	876.5
0436204 1	KLERKSDORP	5/29/2006	15	0	23.2	1.3	81	875.9
0436204 1	KLERKSDORP	5/29/2006	16	0	23.1	1.2	78	876.2
0436204 1	KLERKSDORP	5/29/2006	17	0	20.7	1.5	146	876.4
0436204 1	KLERKSDORP	5/29/2006	18	0	14.9	1.9	134	876.4
0436204 1	KLERKSDORP	5/29/2006	19	0	12.9	0	0	877.1
0436204 1	KLERKSDORP	5/29/2006	20	0	11.9	0	0	877.5
0436204 1	KLERKSDORP	5/29/2006	21	0	11.4	1.2	333	878
0436204 1	KLERKSDORP	5/29/2006	22	0	8.3	0	0	878.1
0436204 1	KLERKSDORP	5/29/2006	23	0	7.9	0	0	878.2
0436204 1	KLERKSDORP	5/30/2006	0	0	6.5	1.3	340	877.9
0436204 1	KLERKSDORP	5/30/2006	1	0	5	0	0	877.9
0436204 1	KLERKSDORP	5/30/2006	2	0	4.6	1.6	330	877.9
0436204 1	KLERKSDORP	5/30/2006	3	0	4.2	2	332	877.6
0436204 1	KLERKSDORP	5/30/2006	4	0	3.7	1.9	332	877.4
0436204 1	KLERKSDORP	5/30/2006	5	0	4	1.1	355	877.4
0436204 1	KLERKSDORP	5/30/2006	6	0	4.1	1.2	340	877.7
0436204 1	KLERKSDORP	5/30/2006	7	0	5	0	0	877.9
0436204 1	KLERKSDORP	5/30/2006	8	0	9.3	1.9	340	878.5
0436204 1	KLERKSDORP	5/30/2006	9	0	13.6	3.4	337	878.7
0436204 1	KLERKSDORP	5/30/2006	10	0	17	3.4	340	879.1
0436204 1	KLERKSDORP	5/30/2006	11	0	20.9	3	338	878.7
0436204 1	KLERKSDORP	5/30/2006	12	0	23.2	2.3	341	878.1
0436204 1	KLERKSDORP	5/30/2006	13	0	24.6	1.5	22	877
0436204 1	KLERKSDORP	5/30/2006	14	0	25	1.6	58	876.5
0436204 1	KLERKSDORP	5/30/2006	15	0	25.1	1.9	145	876
0436204 1	KLERKSDORP	5/30/2006	16	0	24.6	2.6	171	875.9
0436204 1	KLERKSDORP	5/30/2006	17	0	20.9	2.2	148	876.3
0436204 1	KLERKSDORP	5/30/2006	18	0	16.9	1.4	158	876.4
0436204 1	KLERKSDORP	5/30/2006	19	0	15.2	0	0	876.9
0436204 1	KLERKSDORP	5/30/2006	20	0	13.8	0	0	877.3
0436204 1	KLERKSDORP	5/30/2006	21	0	12.8	1.8	246	877.5
0436204 1	KLERKSDORP	5/30/2006	22	0	9.9	0	0	877.7
0436204 1	KLERKSDORP	5/30/2006	23	0	9.2	1.2	324	877.9
0436204 1	KLERKSDORP	5/31/2006	0	0	7	1.9	324	877.9
0436204 1	KLERKSDORP	5/31/2006	1	0	7	2.4	320	878
0436204 1	KLERKSDORP	5/31/2006	2	0	6.2	2.9	326	878
0436204 1	KLERKSDORP	5/31/2006	3	0	6.2	3.1	331	877.9
0436204 1	KLERKSDORP	5/31/2006	4	0	5.4	3.1	333	877.6
0436204 1	KLERKSDORP	5/31/2006	5	0	5.2	2.6	338	877.8
0436204 1	KLERKSDORP	5/31/2006	6	0	4.3	1.5	346	877.9
0436204 1	KLERKSDORP	5/31/2006	7	0	3.5	1.6	341	878.4
0436204 1	KLERKSDORP	5/31/2006	8	0	6.9	1.6	340	879
0436204 1	KLERKSDORP	5/31/2006	9	0	12	1.6	352	879.5

0436204 1	KLERKSDORP	5/31/2006	10	0	16.7	1.5	14	879.7
0436204 1	KLERKSDORP	5/31/2006	11	0	22.3	2	10	879.2
0436204 1	KLERKSDORP	5/31/2006	12	0	23.7	1.7	287	878.7
0436204 1	KLERKSDORP	5/31/2006	13	0	24.7	2.5	169	878
0436204 1	KLERKSDORP	5/31/2006	14	0	25.2	2.6	151	877.4
0436204 1	KLERKSDORP	5/31/2006	15	0	25.3	2.5	154	877
0436204 1	KLERKSDORP	5/31/2006	16	0	24.5	2.5	154	876.9
0436204 1	KLERKSDORP	5/31/2006	17	0	22.3	2.4	154	877
0436204 1	KLERKSDORP	5/31/2006	18	0	18.6	1.9	175	877.4
0436204 1	KLERKSDORP	5/31/2006	19	0	16.6	1.5	199	877.5
0436204 1	KLERKSDORP	5/31/2006	20	0	13.5	0	0	877.9
0436204 1	KLERKSDORP	5/31/2006	21	0	11.9	0	0	877.9
0436204 1	KLERKSDORP	5/31/2006	22	0	11.3	1.5	313	877.7
0436204 1	KLERKSDORP	5/31/2006	23	0	10.1	1.2	308	877.9
0436204 1	KLERKSDORP	6/1/2006	0	0	7.4	1.1	317	877.7
0436204 1	KLERKSDORP	6/1/2006	1	0	5.6	1.1	339	877.7
0436204 1	KLERKSDORP	6/1/2006	2	0	6.1	2.2	331	877.5
0436204 1	KLERKSDORP	6/1/2006	3	0	5.5	3.3	327	877.4
0436204 1	KLERKSDORP	6/1/2006	4	0	5.3	3.5	326	877
0436204 1	KLERKSDORP	6/1/2006	5	0	5.7	3.3	327	876.7
0436204 1	KLERKSDORP	6/1/2006	6	0	5	2.5	333	877.2
0436204 1	KLERKSDORP	6/1/2006	7	0	4	1.2	352	877.6
0436204 1	KLERKSDORP	6/1/2006	8	0	6.5	1.3	353	878.1
0436204 1	KLERKSDORP	6/1/2006	9	0	11.4	1.6	360	878.7
0436204 1	KLERKSDORP	6/1/2006	10	0	17.7	1.8	339	879.2
0436204 1	KLERKSDORP	6/1/2006	11	0	21.5	1.3	360	878.6
0436204 1	KLERKSDORP	6/1/2006	12	0	23	1.2	247	877.9
0436204 1	KLERKSDORP	6/1/2006	13	0	23.9	2.3	183	877
0436204 1	KLERKSDORP	6/1/2006	14	0	24	2.4	165	876.3
0436204 1	KLERKSDORP	6/1/2006	15	0	24.1	2	147	875.9
0436204 1	KLERKSDORP	6/1/2006	16	0	23.8	1.7	151	875.9
0436204 1	KLERKSDORP	6/1/2006	17	0	22	1.5	154	876.2
0436204 1	KLERKSDORP	6/1/2006	18	0	17.3	1.2	185	876.4
0436204 1	KLERKSDORP	6/1/2006	19	0	15.1	0	0	876.5
0436204 1	KLERKSDORP	6/1/2006	20	0	12.5	0	0	876.7
0436204 1	KLERKSDORP	6/1/2006	21	0	9.7	0	0	876.8
0436204 1	KLERKSDORP	6/1/2006	22	0	10.2	1.4	317	876.5
0436204 1	KLERKSDORP	6/1/2006	23	0	9	1.2	273	876.5
0436204 1	KLERKSDORP	6/2/2006	0	0	5.8	0	0	876.3
0436204 1	KLERKSDORP	6/2/2006	1	0	6.4	2.6	325	876.2
0436204 1	KLERKSDORP	6/2/2006	2	0	6.9	3.3	328	875.9
0436204 1	KLERKSDORP	6/2/2006	3	0	6.3	3.2	328	875.7
0436204 1	KLERKSDORP	6/2/2006	4	0	6.4	3	326	875.7
0436204 1	KLERKSDORP	6/2/2006	5	0	5.1	3	331	875.5
0436204 1	KLERKSDORP	6/2/2006	6	0	5.1	2.9	330	875.5
0436204 1	KLERKSDORP	6/2/2006	7	0	3.8	1.5	343	875.8
0436204 1	KLERKSDORP	6/2/2006	8	0	5.6	1.4	329	876.1
0436204 1	KLERKSDORP	6/2/2006	9	0	12.5	0	0	876.3

0436204 1	KLERKSDORP	6/2/2006	10	0	16.5	0	0	876.2
0436204 1	KLERKSDORP	6/2/2006	11	0	20.3	0	0	876.1
0436204 1	KLERKSDORP	6/2/2006	12	0	23.3	1.9	198	875.2
0436204 1	KLERKSDORP	6/2/2006	13	0	24.2	3.4	190	874.4
0436204 1	KLERKSDORP	6/2/2006	14	0	24.7	3.7	214	873.3
0436204 1	KLERKSDORP	6/2/2006	15	0	24.5	3.4	221	873
0436204 1	KLERKSDORP	6/2/2006	16	0	23.9	3.3	205	872.8
0436204 1	KLERKSDORP	6/2/2006	17	0	22.4	3.1	193	873.2
0436204 1	KLERKSDORP	6/2/2006	18	0	18	1.8	204	873.3
0436204 1	KLERKSDORP	6/2/2006	19	0	15.9	1.8	212	873.9
0436204 1	KLERKSDORP	6/2/2006	20	0	13.4	1.4	225	874
0436204 1	KLERKSDORP	6/2/2006	21	0	11.3	1.3	325	874.2
0436204 1	KLERKSDORP	6/2/2006	22	0	7.5	0	0	874.4
0436204 1	KLERKSDORP	6/2/2006	23	0	7.9	1.6	334	874.4
0436204 1	KLERKSDORP	6/3/2006	0	0	7.5	2.2	326	874.1
0436204 1	KLERKSDORP	6/3/2006	1	0	6.3	1.9	323	874.5
0436204 1	KLERKSDORP	6/3/2006	2	0	5.5	1.4	321	874.2
0436204 1	KLERKSDORP	6/3/2006	3	0	4.8	0	0	874.2
0436204 1	KLERKSDORP	6/3/2006	4	0	3.7	0	0	874.2
0436204 1	KLERKSDORP	6/3/2006	5	0	4.7	0	0	874.3
0436204 1	KLERKSDORP	6/3/2006	6	0	7.1	1.4	224	875
0436204 1	KLERKSDORP	6/3/2006	7	0	5.8	1.3	226	876.1
0436204 1	KLERKSDORP	6/3/2006	8	0	7.1	1.6	208	876.9
0436204 1	KLERKSDORP	6/3/2006	9	0	10.3	0	0	877.8
0436204 1	KLERKSDORP	6/3/2006	10	0	12.7	1.7	159	878.2
0436204 1	KLERKSDORP	6/3/2006	11	0	15.9	1.6	71	878
0436204 1	KLERKSDORP	6/3/2006	12	0	18.2	1.8	39	877.3
0436204 1	KLERKSDORP	6/3/2006	13	0	20.2	2.3	57	876.4
0436204 1	KLERKSDORP	6/3/2006	14	0	21.3	2.5	87	876
0436204 1	KLERKSDORP	6/3/2006	15	0	20.7	2.4	102	875.7
0436204 1	KLERKSDORP	6/3/2006	16	0	21.3	2.7	83	875.8
0436204 1	KLERKSDORP	6/3/2006	17	0	19.3	2.8	85	876.2
0436204 1	KLERKSDORP	6/3/2006	18	0	15.9	2.3	72	876.5
0436204 1	KLERKSDORP	6/3/2006	19	0	12.7	0	0	877
0436204 1	KLERKSDORP	6/3/2006	20	0	12.4	1.4	121	878.2
0436204 1	KLERKSDORP	6/3/2006	21	0	11.3	2	101	878.8
0436204 1	KLERKSDORP	6/3/2006	22	0	11.6	3.7	83	879.2
0436204 1	KLERKSDORP	6/3/2006	23	0	10.7	3.1	78	879.2
0436204 1	KLERKSDORP	6/4/2006	0	0	10.4	4.3	72	879.1
0436204 1	KLERKSDORP	6/4/2006	1	0	9.3	2.6	58	879.3
0436204 1	KLERKSDORP	6/4/2006	2	0	9	1.7	49	879.8
0436204 1	KLERKSDORP	6/4/2006	3	0	6.9	1.6	77	880.3
0436204 1	KLERKSDORP	6/4/2006	4	0	6	1.6	108	880.5
0436204 1	KLERKSDORP	6/4/2006	5	0	6.6	1.6	84	880.6
0436204 1	KLERKSDORP	6/4/2006	6	0	6.6	1.3	35	881.3
0436204 1	KLERKSDORP	6/4/2006	7	0	5.4	1.3	79	881.6
0436204 1	KLERKSDORP	6/4/2006	8	0	5.8	0	0	882.2
0436204 1	KLERKSDORP	6/4/2006	9	0	9.8	1.2	44	882.4

0436204 1	KLERKSDORP	6/4/2006	10	0	12.6	1.5	34	882.2
0436204 1	KLERKSDORP	6/4/2006	11	0	15.3	1.7	30	881.6
0436204 1	KLERKSDORP	6/4/2006	12	0	17.4	1.6	11	880.9
0436204 1	KLERKSDORP	6/4/2006	13	0	19.4	0	0	879.7
0436204 1	KLERKSDORP	6/4/2006	14	0	19.4	1.8	148	879.3
0436204 1	KLERKSDORP	6/4/2006	15	0	19.9	1.4	179	878.7
0436204 1	KLERKSDORP	6/4/2006	16	0	19.8	0	0	878.9
0436204 1	KLERKSDORP	6/4/2006	17	0	18.2	0	0	878.8
0436204 1	KLERKSDORP	6/4/2006	18	0	14.7	0	0	879.2
0436204 1	KLERKSDORP	6/4/2006	19	0	12.3	0	0	879.4
0436204 1	KLERKSDORP	6/4/2006	20	0	10.5	0	0	879.7
0436204 1	KLERKSDORP	6/4/2006	21	0	9.5	0	0	879.9
0436204 1	KLERKSDORP	6/4/2006	22	0	8.5	0	0	880.2
0436204 1	KLERKSDORP	6/4/2006	23	0	7.6	0	0	880.2
Limitation								

APPENDIX C

Common Technical and Descriptive Terms

Various names are used to describe airborne particulate matter. The name *particle* refers to a single unit of matter, generally having a density approaching the intrinsic density of the bulk material. Individual particles may be chemically homogeneous or contain a variety of chemical species as well as consist of solid or liquid materials or both. Particle shapes may be simple, as in spherical liquid droplets, or complex, as in fiber bundles or agglomerated smoke. Many of the following terms do not have strict scientific definitions but rather are in common use as merely descriptive terms, often indicating the appearance or source of the particles.

Aerosol: An assembly of liquid or solid particles suspended in a gaseous medium long enough to be observed or measured. Generally, the sizes of aerosol particles are in the range of 0.001 to 100 μm . If the particle concentration is large enough that the density of the aerosol is more than about 1 % greater than the gas alone, the assembly is considered a cloud and has bulk properties that differ from a more dilute aerosol. Note: The technical use of the term *aerosol* is much broader than the every-day usage referring to droplets emitted from a spray can

Bioaerosol: An aerosol of biological origin, including airborne suspensions of viruses, pollen, bacteria, and fungal spores and their fragments

Cloud: A high-density suspension of particles in air, often with a well-defined boundary

Dust: Solid particles formed by crushing or other mechanical breakage of a parent material. These particles generally have irregular shapes and are larger than about 0.5 μm

Fog or Mist: Liquid particle aerosol. These can be formed by condensation of supersaturated vapors or by physical shearing of liquids, such as in nebulization, spraying, or bubbling

Fume: Particles that are usually the result of condensed vapor with subsequent agglomeration. Solid fume particles typically consist of complex chains of submicrometer-sized particles (usually $< 0.05 \mu\text{m}$) of similar dimension. Fumes are often the result of combustion and other high temperature processes. Note that the common usage of *fume* also refers to noxious vapor components

Haze: A visibility-reducing aerosol

Nanoparticle: A particle in the size range of 1 to 100 nm

Particle: A small, discrete object

Particulate: An adjective indicating that the material in question has particle-like properties. Less properly used as a term for particle

Smog: An aerosol consisting of solid and liquid particles, created, at least in part, by the action of sunlight on vapors. The term smog is a combination of the words smoke and fog and often refers to the entire range of such pollutants, including the gaseous constituents

Smoke: A solid or liquid aerosol, the result of incomplete combustion or condensation of supersaturated vapor. Most smoke particles are submicrometer in size

Primary particle: A particle introduced into the air in solid or liquid form. A primary particle is often contrasted to a secondary particle

Secondary particle: Usually a particle formed in the air by gas to particle conversion. This term is sometimes used to describe agglomerated or redispersed particles