THE CONTROL OF DIESEL PARTICULATES IN UNDERGROUND COAL MINES

By

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DECLARATION OF ORIGINALITY OF WORK

This thesis contains no material that has previously been submitted for an award or degree at any university. To my knowledge, the work reported in this thesis is original and contains no material published by other investigations, except where appropriate reference has been given to the source of the material.

Brian Davies

ABSTRACT

The aims of the research for this thesis were fourfold, all of which focused at reducing employee exposure to diesel particulate in underground coal mines. The four aims were to:

a) Develop a method to test disposable diesel exhaust filters and if possible improve their performance

b) Investigate the relationship between maintenance and diesel particulate generation

c) Highlight the benefits of newer design engines in emission reduction

d) Review the research of the Tower Colliery Research group as their findings have been the basis for the development of control technologies for diesel particulate in NSW underground coal mines.

Methods used to achieve these aims involved:

a) The construction of a test rig to measure the efficiency and backpressure of new and used disposable filters

b) The testing of the in-service fleet at four of BHP Billiton Illawarra Coal mines using an R&P Series 5100 diesel analysis system mounted in a trailer

c) Comparison of a newer design engine with three current vehicles under mining conditions

d) A detailed statistical review of all available data from the Tower Colliery Research group.

Key outcomes from research conducted for this thesis are:

a) The filtration efficiency and backpressure of disposable diesel exhaust filters used by BHP Billiton Illawarra Coal have been improved.

These improvements, together with changes to work practices, generate potential cost savings of $395,000 per annum while affording increased protection to equipment operators.

b) Seven engines with unacceptable raw exhaust elemental carbon emissions were identified in a fleet of 66 tested. Some faults identified as causing these elevated emission levels were – blocked exhaust flame traps (scrubber tanks), incorrectly set tappets and worn injectors.

c) Testing of a prototype 4WD fire protected vehicle powered by an “over-the-road” engine as against three current vehicles, highlighted reductions in atmospheric elemental carbon concentrations of 67-90%. Significant reductions in raw exhaust elemental carbon levels were also observed.

d) A statistical review of data produced by the Tower Colliery Diesel Research group identified elevated exposures within mine transportation roadways. This outcome is significant as much research within the mining industry has focused on other areas in the belief that high air quantities in transportation roadways would limit exposures. This does not appear to be the case.

The project has had a number of positive outcomes, all of which have assisted in the reduction of equipment operators to excessive levels of diesel particulate.

ACKNOWLEDGEMENTS

When first encouraged to undertake this thesis I was of the opinion that going back to university after 30 years was all just a bit too hard. After several attempts, Professor John Stearne convinced me that working in industry for 40 years brought with it benefits that many other (and younger) PhD students didn't have. Due to his persistence I relented and after an initial period of adjustment, I have thoroughly enjoyed the experience. I am very grateful for his faith in me to successfully return to university life.

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Steve decided to accept early retirement in September 2003 and he leaves behind a legacy of world's best practice at BHP Billiton Illawarra Coal in regard to the control of diesel particulate.

It goes without saying that projects involving coal mines also involve people and this project was no exception. Many operators, engineers and management personnel have assisted in progressing this project and I would like to thank the management and workforce of Tower, Elouera, Appin, West Cliff and Dendrobium Collieries for their assistance. Microfresh Filters Pty Ltd and 3M Australia Pty Ltd also provided support in producing filters for testing at no cost to the project.

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During the course of my project Sue and I had the unfortunate experience of both our mothers passing away. I hope, in the rest of my life, I can be as good a person as they were.

In their memory I would like to dedicate this project jointly to Beryl Margaret Davies and Olive Eva Louise Hopkins.

I am sure there are others who have helped along the way. I trust they will not be offended if I have neglected to mention them by name but I'm sure they know how grateful I was for their assistance.

Brian Davies

ABBREVIATIONS

ACARP	Australian Coal Association Research Programme
ACGIH	American Conference of Governmental Industrial Hygienists
AIOH	Australian Institute of Occupational Hygienists
ANOVA	Analysis of Variance
BOM	Bureau of Mines (USA)
CANMET	Canadian Centre for Mineral and Energy Technology
Cat	Caterpillar Inc
CDF	Cumulative Distribution Frequency Plot
CMTS	Coal Mines Technical Services Pty Ltd
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DDC	Detroit Diesel Corporation
DDEF	Disposable Diesel Exhaust Filter
DEEP	Diesel Emissions Evaluation Programme (www.deep.org)
DMC	Diesel Man Car
DMR	New South Wales Department of Mineral Resources
DP	Diesel Particulate
EC	Elemental Carbon
EPA	United States Environmental Protection Agency

g/bhp-hr	Grams per brake horsepower hour
g/hr	Grams per hour
g/kWhr	Grams per kilowatt hour
g/MJ	Grams per Mega Joule
H_A	Alternate Hypothesis
HEG	Homogeneous Exposure Group
HEI	Health Effects Institute
Hg	Mercury
H_0	Null Hypothesis
ISO	International Standards Organisation
JCB	Joint Coal Board (Coal Services Pty Ltd)
km	kilometre
kPa	kilopascal
kW	Kilowatt
LCL	Lower Confidence Limit
m^2	square metre
mg/m^3	milligram per cubic metre
mm	millimetre
MPV	Multi Purpose Vehicle
MSHA	Mine Safety and Health Administration

MVUE	Minimum Variance Unbiased Estimate
MWM	Motorenwerke Mannheim AG
NATA	National Association of Testing Authorities
NIOSH	National Institute for Occupational Safety and Health
nm	nanometre
NSW	New South Wales
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
OEM	Original Equipment Manufacturer
OC	Organic Carbon
PAH	Polycyclic Aromatic Hydrocarbons
PET	Personnel and Equipment Transporter
PJB	P J Berriman Pty Ltd
PNA	Polynuclear Aromatic Hydrocarbons
ppm	parts per million
PT	Peak Torque
RCD	Respirable Combustible Dust
RP	Rated Power
R&P	Rupprecht & Patashnick Inc

RPM	Revolutions Per Minute
SAE	Society of Automotive Engineers Inc
SMV	Specialised Mining Vehicles Pty Ltd
TC	Total Carbon
TEOM	Tapered Element Oscillating Microbalance
TSI	TSI Inc
UCL	Upper Confidence Limit
UGAS	Undiluted Gas Analysis System
VERT	Verminderung der Emissioner von Realmaschinen in Tunnelban
WA	Western Australia
µm	Micrometre
Δp	Pressure Differential
4WD	Four Wheel Drive

CONTENTS

CONTENTS (Cont'd)

CONTENTS (Cont'd)

CONTENTS (Cont'd)

CONTENTS (Cont'd)

1. INTRODUCTION

While there is no doubt that diesel particulate was originally generated in the 1890's with the first power stroke of Rudolph Diesel's engine, the characterisation of diesel particulate and the degree of adverse health effects associated with their inhalation has largely remained unresolved for decades.

The issue of diesel particulate or "soot" in industry was essentially neglected until 1988 when the National Institute for Occupational Safety and Health (NIOSH) in the USA published a criteria document (NIOSH 1988) linking occupational exposure to diesel particulate with lung cancer.

As underground miners have worked in close proximity to diesel vehicles since 1927 (Holz 1960) it could be expected that significant research would have been conducted on this potentially high-risk exposure group. This was not found to be the case due to concern that confounding factors such as dusts and radiation would mask any effect from diesel particulate. Research that was undertaken was inconclusive (Reger et al 1982) but was sufficient to suggest that further investigation was required.

This situation changed rapidly after the NIOSH publication in 1988 as regulators and industry sought appropriate means to control the exposure of workers to diesel particulate in underground mines (Ambs and Hillman 1992, Haney 1992, MSHA 1998, MSHA 2001, Schnakenberg and Bugarski 2002).

Research within Australia has centred within the NSW underground coal mining industry. Pratt et al (1993, 1995) highlighted the level of worker exposure to diesel particulate and evaluated a number of potential control technologies, the majority of which had been developed in the USA.

This research resulted in the implementation of a number of control strategies within some sectors of the NSW underground coal mining industry. However, widespread acceptance has been limited due to a number of factors, including ongoing operation costs, a perception that it is a NSW industry issue not an Australian industry issue, an industry reluctance for change and no specific regulatory requirement for control (except duty of care).

While some enlightened operators (Pratt 1998) have reported significant productivity benefits as a result of the control of diesel particulate, many challenges still exist before the industry can claim effective management of diesel particulate.

The aim of this research project was to investigate a number of these issues and search for means by which known control technologies could be made more effective or attractive to industry. In addition the project aimed to revisit research conducted in the early 1990's (Pratt et al 1993, 1995) upon which much of the current approach to the control of diesel particulate in the NSW industry is based, to establish the validity of those early decisions.

While there is no doubt that the majority of research in respect to diesel particulate emissions from underground mining vehicles has been based in the United States and Canada, Australia has played an important role and it is hoped that this project adds to that significant base of local knowledge.

2. REVIEW OF LITERATURE RELEVANT TO DIESEL PARTICULATE

2.1 INTRODUCTION

Over the past 15 – 20 years the scientific literature has documented a wide range of research on diesel emissions, both gaseous and particulate.

More recently the focus has been on diesel particulate, however much of this research has been in the field of toxicology, with specific relevance to the “over-the-road” transportation industry and commercial vehicles, as this is perceived as presenting a significant environmental and health issue.

2.2 DIESEL PARTICULATE COMPOSITION

Holz (1960) discussed the exhaust gas composition of diesel engines used in US underground non-coal mines and tunnels and observed that smoke being emitted from a diesel engine was in two forms. The first form occurred upon starting of a cold engine where a blue haze was frequently observed and usually decreased in intensity as the engine warmed up. This was attributed to unburned or partially burned fuel. The second form occurred as the load on the engine was increased into the operating range whereby the exhaust became grey when viewed in transmitted light. The grey appearance was attributed to carbon particles in the exhaust, the colour of which changed to black if the fuel:air ratio was increased.

Holz concluded that the presence of this black smoke was an indicator that excessive quantities of carbon monoxide were present in the exhaust and that adjustment to the maximum fuel injection rate was necessary.

Although soot had been identified in the exhaust of diesel engines used in underground mines (Holz 1960), it was not until the mid 1970's that the characteristics of diesel particulate were resolved.

Amman and Siegla (1982) summarise the research on this aspect and define diesel particulate as "consisting principally of combustion generated carbonaceous soot with which some unburned hydrocarbons have become associated". Using photomicrographs of the exhaust from a diesel passenger car, Amman and Siegla (1982) demonstrated that diesel particles were made up of a collection of basically spherical primary particles called "spherules" which were agglomerated into aggregates ranging in appearance from resembling a cluster of grapes to resembling a chain of beads. Amman and Siegla (1982) suggest that the spherules vary in diameter between 10 and 80 nm with most in the 15 – 30 nm range.

Studies within coal mines (McCawley and Cocalis 1986, Cantrell and Rubow 1991) has demonstrated that the majority of diesel particulate experienced in underground atmospheres has a diameter typically <1 μm which is in the human respirable range (ISO 7708).

Amman and Siegla (1982) further goes on to discuss how these very fine particles (typically <1μm) have the ability to absorb significant quantities of hydrocarbons thought to be originating from the fuel, lubricating oils and the complex chemical reactions in the cylinder. This ability to absorb chemical compounds was the basis for concern in regard to adverse health effects, however subsequent research suggested an alternate mechanism.

Traces of inorganic compounds were also found in the particulates, eg sulphur, zinc, phosphorous, calcium, iron, silicon and chromium. These were attributed to have arisen from the fuel and additives to the lubricating oil used in the engine.

In summary, diesel particulate has the following characteristics.

- Consist primarily of small particles (15 – 30 nm) called spherules, which agglomerate to form larger particles, which are typically less than 1 μm in diameter.
- Have the ability to absorb significant quantities of hydrocarbons and other organic compounds.
- Have traces of inorganic compounds.
- Are in the size range for human respirability.

2.3 HEALTH EFFECTS OF DIESEL PARTICULATE

The potential for adverse health effects arising from occupational exposure to diesel particulate has been the subject of intense scientific debate for the past 25 years. One of the first reports of the carcinogenic potential of diesel emissions was by Kotin et al (1955) who demonstrated that skin papillomas and cancers developed when acetone extracts of the particulate matter found in diesel engine emissions were painted onto the skin of mice. These findings did not receive much attention and it was not until Ames et al (1975) introduced a short term bacterial mutagenicity assay (which was adopted by the scientific community as a tool to predict carcinogenicity) that further evidence was reported.

In 1978 several researchers (Huisingh et al, Wang et al) reported that organic solvent extracts of diesel exhaust particulate matter produced mutations in bacteria.

Research in the 1980's focused on identifying the potentially hazardous constituents of diesel particulate. This research identified hundreds of chemicals of which polycyclic aromatic hydrocarbons (PAHs) received particular attention due to their potent mutagenic and carcinogenic potential (IARC 1989).

Westerway and Faulds (1982) measured PAH levels in five underground mines in Canada and found reasonably high concentrations, albeit less than that found in large cities.

Westerway and Faulds (1982) demonstrated that PAH concentrations were affected by factors such as distance from the diesel, type of ore mined, size of the mine drift, type of explosive used, the design of the mine, the type of catalytic converter used, the fuel used and possibly the type of diesel engine used.

Consequently research as to the health effects of diesel particulate was guided through the 1980's on the basis that they were a carcinogenic hazard because they contained potential mutagens and carcinogens adsorbed onto the surfaces of particles. These particles were in a size range that allowed them to be inhaled into the deep regions of the lungs, thus allowing the adsorbed chemicals to be taken up by the body, interact with DNA and initiate carcinogenesis. Concern as to the bioavailability of these chemicals dominated toxicological research at the time.

In the 1980's and early 1990's a number of animal bioassays were conducted by independent research groups (Heinrich et al 1986, 1995; Inhinski et al 1986; Iwai et al 1986; Mauderly et al 1987, 1994; Brightwell et al 1989).

The findings of all these groups were consistent and suggested that if diesel exhaust was inhaled at high concentrations for periods in excess of 24 months, lung tumours were prevalent in rats. Some studies compared raw exhaust to filtered exhaust and only found tumorigenic effect from the raw vapour phase thus implicating the particulate phase.

These findings prompted two research groups to investigate the contribution of particles in diesel exhaust in the development of tumours in rats. Mauderly (1992) and Heinrich et al (1995) both reported that when inhaled at high concentrations for prolonged periods both diesel particulate and chemically inert carbon black (no adsorbed chemicals present) induced tumours in rats.

These findings suggested that the adsorbed carcinogens on the diesel particulate were not the cause of tumours in rats and that the particulate itself might play a more dominant role in the carcinogenic pathway.

This outcome is confounded by the fact that negative results were found in mice and hamsters. This has led to the suggestion that the carcinogenic process in the rat does not appear to involve absorbed carcinogens or mutagens, as had been previously hypothesized. Instead, the process appears to involve particle overload at very high concentrations, as no carcinogenic effect is observed at lower particle concentrations. Some researchers (HEI 1995, Mermelstein 1994) consider that the overload mechanism observed in rats may not be applicable to humans who are generally exposed to much lower concentrations that produce no particle overload of the lung.

Nevertheless, the work of Mauderly (1992) focused attention on elemental carbon as a potential carcinogen, with a resultant upsurge in research.

In the 1950's epidemiologists began to study the relationship between lung cancer and occupational exposure to diesel exhaust (Raffle 1957).

In the period since 1957 many studies have been undertaken mainly in the transportation industry (rail workers, bus/garage workers). While underground miners represent a relatively high exposure group to diesel particulate (Haney 1992) they generally have not been targeted for epidemiologic studies due to their exposure to other contaminants (eg dusts).

In the mid 1990's the Health Effects Institute (HEI), a joint government-industry research group in the USA, established a Diesel Working Group to review the research that had been conducted on the health effects of diesel emissions.

After reviewing in excess of 30 epidemiological studies of workers exposed to diesel emissions in occupational settings for the period 1950 to 1980 HEI (1995) concluded that:

> *"The epidemiologic data are consistent in showing weak associations between exposure to diesel exhaust and lung cancer. The available evidence suggests that long-term exposure to diesel exhaust in a variety of occupational circumstances is associated with a 1.2 to 1.5-fold increase in the relative risk of lung cancer compared with workers classified as unexposed."*

The HEI did sound a note of caution due to the lack of definitive exposure data and an inability to determine the influence of confounding factors.

The two key epidemiological studies commonly quoted in the literature are those of Garshick et al (1988) (rail workers) and Steenland, Silverman and Zaebst (1992) (truck drivers). Garshick et al (1988) found a significantly increased risk of lung cancer of 1.4 (1.06 – 1.88, 95% CI) and Steenland, Silverman and Zaebst (1992) found an increased risk of lung cancer of 1.3 (0.81 - 2.21, 95% CI).

A critical review of these two studies, has determined that they have different validities. (HEI 1995)

In respect to the US railway workers study (Garshick et al 1987, 1988), the HEI found an increased lung cancer risk in groups such as train workers, shop workers and clerks, however these risks were not found to be dose related.

In fact, the risk decreased as duration of exposure (and hence increasing cumulative exposure) increased (Crump, Lambert and Chen 1991). HEI suggested that since the dose response was negative in all three occupational categories, some form of bias is present in the data. They went on to suggest that this bias may have resulted from uncontrolled confounding by cigarette smoking, by other occupational exposure agents, misclassification of occupational groups or other factors.

In regard to the truck drivers study (Steenland, Silverman and Zaebst 1992), HEI concluded that the study had a weakness in that it used estimates to reconstruct past exposures. Concern was expressed that these estimates most likely under-estimated exposures in the early years as they were based on general trends in truck usage, fuel and emission rates.

Overall, HEI concluded that, based on the identifiable deficiencies in these two studies, that either individually or in combination, they did not provide adequate data for quantitative risk analysis. Recommendations were made for the development of additional studies designed to resolve the epidemiological issue.

Some epidemiologic studies have suggested that an elevated risk of bladder cancer may be linked to diesel exhaust exposure in occupational environments. The evidence for bladder cancers is however not as consistent as lung cancer.

As indicated by the HEI (1995) a significant number of epidemiologic studies of diesel exhaust have been criticised due to the failure by researchers to correct for confounding factors (eg smoking, other contaminants) and to the complete lack of diesel particulate exposure data from the period when the workers being evaluated were exposed.

Given these factors, two research groups, Bhatia, Lopipero and Smith (1998) and Lipsett and Campleman (1999) set out to conduct a comprehensive statistical “meta-analysis” of the epidemiologic literature. The meta-analysis process aims to systematically combine the results of previous studies in order to generate a quantitative summary and to examine the influence of sources of variability among studies. In both cases Bhatia, Lopipero and Smith (1998) and Lipsett and Campleman (1999) concluded that the meta-analysis supported a causal association between increased risk of lung cancer and exposure to diesel exhaust. However, some discussion has previously occurred in the treatment of negative outcomes in meta-analysis epidemiological studies (Stober and Abel 1996, Cox 1997, Morgan, Reger and Tucker 1997) which gives rise to some concern as to the validity of the conclusions of these studies.

Two reviews (NIOSH 1995, IARC 1997) indicate that most studies show that coal miners have a lower than expected risk of developing lung cancer. No information was available to determine the extent, or effect if any, of exposure to diesel particulate in these studies.

A large scale investigation into cancer risk in the NSW coal industry was completed in 1994 and updated in 1997. This involved matching the employment medical records with the records of the NSW Central Cancer Registry of 23,630 men who entered the industry at or after 1973 up until the end of 1992. The overall standardised cancer incident ratio was lower than the general population (0.82 95% CI 0.73-0.92).

For lung cancer the rate was much less than the normal (SIR 0.74 95% CI 0.50-1.06) (Christie 1994, Brown et al 1997). Although it is certain that all underground workers in the cohort had at some stage been exposed to diesel particulate, it is not possible to determine what influence exposure to diesel particulate or other factors had on the study outcomes.

More recently both MSHA (2001) and the New South Wales Joint Coal Board (1999) have indicated that they consider diesel particulate to be a potential carcinogen. The Joint Coal Board's Chief Medical Officer states "Diesel particulate may be cancer-causing, possibly at the risk level of passive cigarette smoking exposure".

In May 2002 the United States Environmental Protection Agency (US EPA) published their health assessment for diesel engine exhaust (US EPA 2002).

The stated aim of the document was to identify and characterise the potential human health hazards of diesel exhaust and to estimate the relationship between exposure and disease response.

The US EPA (2002) concluded that diesel particulate matter was the most appropriate parameter of total diesel exhaust to correlate with human health effects until more definitive information about the mechanisms of toxicity or mode of action become available.

In regard to health effects the US EPA based their conclusions on diesel engines built prior to the mid 1990's and suggested they fell into three categories. These were:

- Acute Effects
  Eye, throat and bronchial irritation, light headedness, nausea, cough and phlegm.

- Chronic Non-cancer Respiratory Effects
  Based on animal evidence the potential existed for chronic respiratory disease.

- Chronic Carcinogenic Effects
  Lung cancer was evident in occupational exposed groups and was thought to be a hazard at lower environmental exposures.

The US EPA also sounds a warning by pointing out the many uncertainties that exist due to assumptions being used to bridge data and knowledge gaps.

Because these gaps had been evident for some time the HEI (2002) funded six diesel feasibility studies in the period 1998 - 2000 to provide information on potential study populations and on exposure assessment methods.

At the end of an extensive review, HEI concluded that it could not recommend that funding be made available for a new cohort study due to continuing methodologic and data challenges. The HEI did propose that a workshop be held to plan approaches for exploring emissions and monitoring data to identify components (signatures) which could be used in epidemiologic assessments of exposure. This workshop was held in December 2002 by the HEI (2003) and while it highlighted many research opportunities no conclusion on a definitive exposure marker (signature) eventuated.

A project with relevance to the mining industry is that being undertaken by Dahmann (2003) in Germany. Here a longitudinal epidemiological study is being undertaken at two underground salt/potash mines with the focus being on lung issues. To date no results have been published.

Notwithstanding these studies, evidence suggests that potential significant irritation effects exist within work groups exposed to high levels of diesel particulate and/or diesel emissions.

In many cases regulatory authorities in the USA, Europe and Canada have concluded that sufficient evidence exists to indicate that diesel particulate does present an increased risk of lung cancer, however in many instances the quantification of potency has been, and continues to be, an area of intense debate. Given this situation of scientific uncertainty, many organisations have adopted a policy of caution and support the minimisation of employee exposure wherever possible.

Adoption of this strategy within the Australian underground coal mining industry has produced reduced employee irritant effects and increased productivity, however the issue of whether this results in a reduced lung cancer outcome remains unresolved.

2.4 METHODS OF ANALYSIS

Based on the need to control diesel particulate, research has been underway for a substantial period to establish reliable methods of estimating worker exposures. Initial approaches to monitoring diesel particulate followed that which had historically been used to monitor respirable dust. Up until the early 1970's the contribution of combustible material "soot" had been recognised as being a significant proportion of the respirable dust fraction but no action was taken to quantify this fraction.

In 1971 a major metalliferous mining company in Canada (Stachulak and Conrad 1998) participated in a research project to measure the combustible fraction of the respirable portion of airborne dust. The method was optimised over several years and resulted in the monitoring technique "Respirable Combustible Dust" or RCD.

The technique involves the collection of respirable dust on a silver membrane using a miniature cyclone. The filter is weighed prior to heating in a furnace for one hour at 400°C. The filter is re-weighed with the amount of material being lost deemed RCD. This method has found substantial support, especially in the metalliferous mining industry, however its application to coal mines has not been possible due to its dependence on the combustion of material of which a proportion would be coal dust.

The NSW Department of Minerals and Energy (1989) used a similar approach but incorporating glass fibre filters and a low temperature plasma asher.

In relation to diesel particulate monitoring in coal mines, McCawley and Cocalis (1986) proposed that existing respirable dust monitoring devices be modified with a single-stage impaction pre-separator to separate diesel particulate, which had previously been demonstrated to be less than 1 μm (Amman 1982), from respirable coal dust.

This concept was fully investigated by Cantrell and Rubow (1992) who demonstrated that a bimodal distribution of aerosol average mass size occurred in dieselised mines.

The cut point between the two size fractions was relatively sharp and occurred at approximately 0.8μm. Using this criteria Cantrell and his colleagues proceeded to develop a “Personal Diesel Aerosol Sampler” which consisted of a normal respirable dust cyclone followed by a second stage multiple nozzle impactor with a cut size that only passes aerosol with less than 0.8μm aerodynamic diameter.

The less than 0.8 μm aerosol was collected on a Teflon filter and determined gravimetrically. The sampler operated at 2 litres/minute and was designed to be compatible with commercial sampling pumps used in the mining industry.

This instrument has been used from the early 1990's and has been found to be very effective where workplace exposures provided sufficient deposit for accurate gravimetric analysis. Rogers, Davies and Conaty (1993) demonstrated, using electron microscopy, that there was less than 10% positive interference due to non-diesel particulate matter providing that the respirable dust levels were kept below about 3 mg/m^3.

The work of Mauderly (1992) and Heinrich et al (1995) shifted the focus from monitoring whole diesel particulate to the analyte of interest, ie elemental carbon. In this regard Birch and Cary (1996) proposed a thermal-optical technique for the analysis of the carbonaceous fraction of diesel particulate.

This technique provided separation of organic and elemental carbon through the careful control of temperature, which provided significant benefits as diesel exhaust is the only significant source of elemental carbon. This method has achieved widespread acceptance and is now commonly referenced as NIOSH Method 5040 (1994).

A similar approach has been adopted in Germany, however sampling is conducted without any size separation and analysis of combustible carbon is via a coulometric method (Dahman and Bauer 1997). The lack of size selection in this method limits the method to those mining applications where combustible material is not present.

Commercialisation of these methods has been speedy with Sunset Laboratories in the USA developing instrumentation for NIOSH Method 5040 (1994), Strohlein developing a coulometric instrument in Germany and recently SKC Inc (2001) in the USA developing a disposable diesel particulate sampling device.

The validity of this disposable device has not as yet been justified in the scientific literature, however considerable research in this area is currently in progress with excellent results reported (Rogers 2003).

A recent study in Canada by Verma et al (2003) concludes that the thermo-optical method (NIOSH Method 5040) for elemental and organic carbon is the most valid technique to evaluate diesel particulate at the present time. Verma also supports the use of cyclones as proposed by Cohen et al (2002) rather than open faced sampling heads.

Considerable research on the applicability of elemental carbon as a measurement technique for occupational exposure in the Australian coal industry has been conducted by Rogers and Whelan (1996) and Rogers and Davies (2001). This work has supported previous work (Pratt et al 1993, 1995) in that it has identified longwall changeouts as the period of highest exposure.

While there has been considerable focus on the measurement of workplace exposure to diesel particulate, the measurement of raw exhaust levels has been somewhat slower. Historically, measurement of “soot” in the raw exhaust of diesel engines used in underground mines has been via gravimetric means using dilution tunnels and dynamometers (MSHA 1996).

In the Australian coal mining industry reliance has been on the use of the Bosch Smoke Meter, otherwise known as the Sampling Opacity Meter (AS3584.2 : 2003). This Australian Standard required engines not to exceed specific light absorption coefficients based on the nominal gas flow (in litres/second) of the engine.

It is interesting to note that the US Bureau of Mines (Daniel 1998) investigated the use of the Bosch Smoke Meter to measure particulates from diesel engines used in mines and concluded that although good precision was obtained on a number of tests the Bosch Smoke Meter was not useful at low load conditions due to a lack of sensitivity.

This conclusion appears to be in direct conflict to the Australian Standard where the nominated test procedure requires Bosch Smoke Meter tests at no load (both low and high idle speeds) and full load.

Another approach has been adopted by Davies (2000) who used an elemental carbon analyser (Okrent 1996) to determine the levels of raw exhaust elemental, organic and total carbon in the raw exhaust of vehicles used in Australian coal mines.

This work highlighted the wide variability of raw exhaust particulate concentrations and indicated that certain engine types generated excessive levels of particulates. Other techniques are available e.g. TEOM (Shore and Cuthbertson 1985), but they have never been applied to a mining situation for diesel emission analysis.

In recent years there has been considerable scientific debate as to the role of ultrafine and nanoparticles generated from newer diesel engines as against older designs.

This has also led to a debate on the measurement of particulates in the raw exhaust of diesel engines.

This debate is best summarised by Kittelson (2001) who highlights the fact that unlike carbonaceous soot particles associated with older diesel engines, these ultrafine particles are formed by gas to particle conversion processes from vapour phase particle precursors as the exhaust of newer design engines dilutes and cools in the atmosphere. Kittelson concludes that nanoparticle measurements are very strongly influenced by the sampling and dilution techniques employed. Much more work needs to be performed on these issues before a validated method for raw exhaust could be established.

Given this uncertainty, it appears logical that a monitoring technique (Davies 2000) which measures the parameter in diesel particulate (i.e. elemental carbon) thought to cause lung cancer, is the most appropriate to adopt for use in research projects at this time.

2.5 WORKPLACE EXPOSURE STANDARDS

The development of a workplace exposure standard for diesel particulate is still in progress. Historically, Canada and Germany were the first to introduce statutory limits for diesel particulate in underground mines.

These limits were 1.5 mg/m^3 in Canadian non-coal mines (Watts 1992) and 0.6 mg/m^3 for German non-coal mines (Dahman and Bauer 1997).

The exposure standard for diesel particulate in Canadian mines however has remained constant over the years, with most Canadian provinces having a respirable combustible dust standard (RCD) of 1.5 mg/m^3. This is expected to change in 2003 (Grenier 2003) with Quebec moving to 0.6 mg/m^3 (RCD) and Ontario 0.4 – 0.6 mg/m^3 (RCD). These values appear to have been set based on the lower limit of detection of the RCD method rather than on a dose response relationship.

A similar approach has also been adopted with NSW metalliferous mines where a value of 2 mg/m^3 respirable combustible dust was in force (NSW Department of Mineral Resources 1996) until it was revoked without replacement.

The German mining industry has also had a long association with regulatory authorities in the development of exposure standards. Their approach has been to develop a technical rule for toxic substances (or TRGS) rather than a dose response exposure standard. In underground non-coal mining and construction activities this is set at 0.3 mg/m^3 elemental carbon. In regard to coal mines, the potential level of particulates in every production site is calculated from vehicle emission and ventilation rates (Dahman 2003). If the value of 0.3 mg/m^3 elemental carbon is exceeded, steps are taken to either reduce the number of machines or increase ventilation levels.

The American Conference of Governmental Industrial Hygienists has proposed a number of draft standards ranging from 0.05 – 0.15 mg/m^3 diesel particulate with no clear indication as to the monitoring technique.

This latest draft standard (ACGIH 2002) proposes a value of 0.02 mg/m^3 and suggests that total carbon is approximately equal to 85% of diesel particulate matter and 30 – 70% for elemental carbon (ACGIH 2000). In 2003 (ACGIH 2003) this value was removed, without explanation, from the list of intended changes.

In 1998 the US Mine Safety and Health Administration (MSHA 1998) proposed an exposure standard of 0.16 mg/m^3 total carbon and suggested that this was equivalent to 0.2 mg/m^3 whole diesel particulate matter.

It is interesting to note that coal mines have been excluded from these proposed standards due to the difficulties in analysis (i.e. carbon from diesel particulate in the presence of carbon from coal).

To overcome this problem the US Mine Safety and Health Administration promulgated a raw exhaust standard of 2.5 g/hr (MSHA 2001). This standard is only applied at the engine approval stage and is not measured in routine service but used as a guide by operators to develop effective control strategies.

As the result of legal action a negotiated agreement has been reached with MSHA (2002) in regard to workplace exposure standards in metal and non-metal mines. The agreed standard is 0.4 mg/m^3 total carbon for an interim period, concluding on 20 January 2006, when the standard reverts to the 1998 proposal of 0.16 mg/m^3 total carbon.

In August 2003 (Federal Register 2003) MSHA issued a notice indicating that the final permissible exposure limit for underground metal and non-metal mines would be based on elemental carbon rather than the previously proposed total carbon.

This change in direction appears to be linked to interferences observed in a 31 mine evaluation study where drill oil mist and environmental tobacco smoke in personal samples added to the overall total carbon content. Based on a stance that elemental carbon makes up 77% of total carbon content of diesel particulate, the current (to 2006) exposure standard is 0.308 mg/m^3 elemental carbon and future (post 2006) exposure standard is 0.123 mg/m^3 elemental carbon. To determine compliance a further error factor of 1.12 and 1.15 is applied to the respective exposure standards.

The NSW Minerals Council (1999) has proposed an industry best practice exposure standard of 0.2 mg/m^3 (as DP) which is based on minimisation of irritation. The Minerals Council acknowledges that although compliance with such a standard would offer substantial improvement for workers, there is insufficient evidence to suggest such a standard would prevent the development of diseases such as cancer.

The Minerals Council publication goes on to suggest that worker exposure levels to diesel particulate should be reduced as low as reasonably practicable through effective control strategies.

2.6 CONTROL TECHNOLOGIES

The control of diesel particulate from engines used in the underground mining industry has presented a number of unique challenges that have been investigated over the past 15 years. Historically, mining industry focus has been on gaseous emission control through adequate ventilation, statutory workplace and raw exhaust gas monitoring, together with control devices such as catalytic converters.

Particulate control in underground coal mines was not the subject of significant research until the late 1980's when a NIOSH publication (NIOSH 1988) linked occupational exposure to diesel particulate to lung cancer, and forced US regulators to initiate investigations into potential control technologies.

In late 2002 the Pittsburgh Research Laboratory of NIOSH (Schnakenberg and Bugarski 2002) released a review of technology available to control diesel emissions in the underground mining industry.

This document aims to present the performance and limitations of control technology designed to reduce diesel exhaust emission (both gaseous and particulate) from the exhaust pipe of engines used in underground mines.

The range of technologies considered for use in coal mines includes: low emission engines, de-rated engines, fuels, fuel additives, catalytic converters, particulate filters and maintenance.

This document focuses almost exclusively on work performed in North America with some mention of European research. No reference is made to the substantial amount of research performed within the Australian coal mining industry. The contribution of Australia to the understanding of this complex issue is included in the following sections on specific control technologies.

2.6.1 Fuel Quality

Perhaps the most intensively investigated parameter is that of fuel quality as it was considered that improved fuel quality may offer an easy solution to the problem of particulate generation. Ryan et al (1981) summarised the properties of fuel known to effect exhaust smoke (particulates). These were boiling range, viscosity, specific gravity, aromatics, hydrogen content and cetane number.

It is interesting to note that no mention was made as to the influence of sulphur which was not established until Ullman (1989) developed a fuel matrix which allowed the effects of sulphur content, aromatics, 90% boiling point and cetane number to be investigated.

The outcome of Ullman's research was that lowering fuel sulphur content to 0.05% resulted in a reduction of diesel particulate levels by about 10% and an increase in cetane number from 45 to 55 reduced hydrocarbons by 60%, carbon monoxide by 45%, oxides of nitrogen 6% and particulates 20%.

Graboski (1992) provides an excellent summary of research on this topic and concludes by suggesting that sulphur control, cetane number, aromatic content and possibly oxygen addition could reduce exhaust particulate levels by up to 25%.

Within the Australian coal mining industry three studies on fuel quality have been carried out. These were conducted under varying conditions by Robinson, Demaria and Mitka (1990), Pratt et al (1993), (1997) and Humphreys et al (1998). The conclusions of these three reports are somewhat diverse. Robinson concluded that Australian diesel fuels produced more “soot” than US fuels and attributed this to higher aromatic content and to increased levels of higher boiling point components (above 338°C) in Australian fuels. Pratt initially considered that the relationship between fuel quality and diesel particulate was inconclusive due to the errors involved with sampling and analysis.

Subsequent work (Pratt et al 1997) suggests a reduction of 10-15% in particulate levels and a significant reduction in odour when using low sulphur fuel. Humphreys et al (1998) concluded that the most significant fuel property affecting emissions was density.

Notwithstanding this diversity of opinions the NSW Minerals Council (1999) recommended that mining companies should consider purchasing low sulphur fuel as part of their strategy for the control of diesel particulate due in part to the fact that the work of Pratt et al (1993, 1997) was based on workplace monitoring not dynamometer testing as used by Robinson, Demaria and Mitka (1990) and Humphreys et al (1998).

2.6.2 Ventilation

Over the past 50 years the control of gaseous emissions in underground coal mines has essentially relied on ventilation. This has resulted in the establishment of prescribed standards for air quantities flowing over engines.

In NSW this value is 0.06 m^3/s/kW (NSW Coal Mines – Underground Regulation 1999) and is applied to each piece of equipment (in an additive manner) which is operating in a section of a coal mine.

This sets the minimum ventilation rate for the operation of diesel equipment in that section.

In the United States the statutory ventilation rate is determined at the engine approval stage by the Mine Safety and Health Administration. Ventilation rates for each engine are determined by a standardised test cycle and are calculated as the quantity of air required to reduce the exhaust concentration to the 1972 American Conference of Governmental Industrial Hygienists threshold limit value (a workplace exposure standard) (MSHA 1996). This is known as the “approval plate quantity” and allowance must be made for this quantity of air to be present for each engine in a section of a mine. While the control of gaseous emissions via ventilation is well defined, little information exists on the quantity of air necessary to control diesel particulate.

Pratt et al (1995) demonstrated that the relationship of diesel particulate to ventilation was very complex and not well understood.

Furthermore it was demonstrated that large diesel engines operating in relatively small roadways at minimum airflows resulted in thermal stratification of the airway, thus potentially concentrating diesel particulate in the upper one-third of the roadway (which is approximately at head height).

The NSW Minerals Council (1999) has suggested the use of vehicle control systems or “tag boards” which effectively restrict the number of vehicles in a section of a mine.

The mechanism for this approach is to assign one or more tokens to each vehicle (based on the statutory airflow requirement) and to routinely measure the airflow in the mine section in question to establish how many “tokens” can reasonably be permitted to enter.

Thus, once all the tokens on the tag board are exhausted no further vehicles can enter the section until a vehicle leaves and the appropriate number of tokens becomes available.

To overcome the uncertainty surrounding the correct ventilation rates to apply, the US Government has adopted a unique approach whereby they developed a “particulate index”. This value is the quantity of air required to reduce the level of diesel particulate in the raw exhaust of an engine to 1 mg/m^3 (MSHA 1996).

While this produces an arbitrary ventilation rate for each engine design it does allow comparison of engine types in terms of their “dirtiness”. The particulate index is also used to develop a ventilation plan for each mine.

From the available literature it is apparent that the relationship between ventilation and diesel particulate is not well understood, although attempts have been made to better understand the process via the use of computer models (Wan, Mutmansky and Ramani 1995).

2.6.3 Exhaust Treatment Devices

Post engine exhaust treatment devices have been the subject of substantial research and development over the last 40 years.

The forerunner of this type of control technology was the catalytic converter and as far back as 1960 (Holz 1960) catalytic converters were recognised as being excellent in reducing the level of carbon monoxide in the exhaust of a diesel engine.

At this early stage it was also recognised that catalytic converters were of limited use in reducing oxides of nitrogen and no mention was made in regard to particulates.

In 1977 (NIOSH 1982) an international joint industry-government working group evaluated the benefit of catalytic converters and water scrubber tanks (used to control sparks from engines).

As predicted there was a significant reduction in carbon monoxide, hydrocarbons and odour with catalytic converters but virtually no reduction in oxides of nitrogen or particulates.

Scrubber tanks on the other hand offered no reduction in carbon monoxide or oxides of nitrogen but some reduction (approximately 30%) in carbonaceous particulates.

This reduction in particulates using water baths has recently been confirmed (Pratt et al 1995).

As water baths are one statutory option in NSW coal mines (AS3584.2 : 2003, NSW Department of Mineral Resources 1995) it can be concluded that all vehicles fitted with such devices are achieving a 20-30% defacto reduction in particulates from that present in the raw exhaust.

Ceramic wall flow particulate filters have found increasing use in the US and Canadian metal/non-metal mines (Waytulonis 1992), however their requirement for an exhaust temperature of greater than 400°C for regeneration excludes them from use in coal mines.

This exclusion is based on two parameters, i.e. a statutory requirement that all surfaces and exhaust gases not exceed 150°C (AS3584.2 : 2003) and the potential for uncontrolled regeneration resulting in excessive levels of carbon monoxide (Currie 1994).

While regenerative exhaust filters are not an option in underground coal mines other approaches to removing the particulate from the exhaust of diesel engines have been explored.

Mogan and Dainty (1987) investigated the use of a venturi water scrubbing system which reduced particulate levels by 65-75%, however this system has not been commercialised. Ambs and Hillman (1992) reported on the development of low temperature post scrubber tank disposable filters. Reductions in diesel particulate levels, measured in the mine atmosphere, of 93-98% were achieved with a filter life of approximately 10 hours. Filter life was severely compromised by water saturation as a result of carryover from the water-filled scrubber tank.

Safety concerns were also expressed by Ambs due to the fact that the filters were made of paper and if the engine shutdown system failed - resulting in a loss of water in the scrubber tank - exhaust temperatures could rise to levels where ignition of filters and collected particulate matter was possible. MSHA (2003) issued a notice recommending that paper filters not be used unless an adequate shutdown system was fitted to the vehicle and fully maintained.

Pratt et al (1995) further developed this concept by using a woven polypropylene material that melted at 170°C but did not support combustion. This product had the added advantage of not being subject to degradation from water.

Tests indicated reductions, as measured in an underground test station, of up to 80%. This concept has since been commercialised and is in common usage within the NSW coal mining industry.

Other filter media have been explored (Bickel and Taubert 1995) such as lava rock and woven fibreglass. The lava rock resulted in collection efficiencies of approximately 35% while the woven fibreglass was approximately 70-85% efficient. Neither of these products appears to have progressed to commercial status.

Recent regulatory events in the USA (MSHA 2001) have resulted in the need for coal mine operators to routinely use disposable exhaust filters to meet the statutory exhaust limit of 2.5 g/hr.

Exhaust dispersion devices have, in the past, been used within the mining industry as a control device (Lowndes and Moleney 1996). While a tenfold dilution of raw exhaust emissions has been recorded, the fact remains that this is a dilution rather than a removal process and thus these devices do not alter the amount of diesel particulate in the general mine atmosphere.

2.6.4 Engine Decoking

Another novel approach to minimising the generation of diesel particulate has been reported by Pratt et al (1995). This approach involves the use of a chemical decoking agent that is circulated with diesel fuel for a period of 30-45 minutes while the engine is operating. The chemical decokes injectors and removes coke build-up from within the cylinders thus allowing better combustion.

The result of this improved combustion is a decrease in particulate generation of up to 15%, which appeared to be sustainable for up to 10 months before recoking occurred.

2.7 ENGINE DESIGN AND MAINTENANCE

Perhaps the two areas that offer the greatest possibility for reduction in diesel particulate are engine design and maintenance, both of which do not appear to have been fully evaluated or developed in regard to underground coal mines.

Waytulonis (1992) reports on research at the US Bureau of Mines where the emissions from a normally aspirated diesel engine (Caterpillar 3304) of 1979 vintage was compared to a 1991 electronically controlled engine (DDC 8V-92TA).

Under the same test conditions the Caterpillar 3304 engine produced an average of 0.11 g/MJ while the DDC engine only produced 0.052 g/MJ; a reduction of approximately 50%. Electronic controlled engines achieve this reduction in particulates by continually optimising the fuel injection timing and rate to match each power requirement during the operation cycle of the engine. In essence such electronically controlled engines are always in tune.

These newer designed engines are common within the metalliferous mining industry but are not presently allowed in underground coal mines due to their lack of intrinsic safety (.ie. the essential ability of an engine to ensure that an explosion of elevated levels of mine gases, e.g. methane, will not occur).

Consequently, the coal industry continues to use 30 year old designed engines with Caterpillar engines accounting for 52.9% (NSW Mineral Resources 1999) of all engines used in NSW underground coal mines.

The substantial benefits of newer designed engines (albeit not electronically controlled) has been demonstrated by Davies (2000) who compared the emissions from mine transport vehicles to that of commercial over-the-road vehicles. In this case a KIA diesel engine (50 kW) was compared with a Toyota Landcruiser Series 75 engine (95 kW) with the total carbon output of the KIA engine ranging from 0.33-1.7 g/kWh to 0.005-0.09 g/kWhr for the Toyota engine.

While Davies (2000) acknowledges that direct comparisons are difficult due to the different engine system used in mine vehicles, it would be anticipated that engines of newer design offer substantial benefits in emission reduction, especially given the pressure being applied by regulatory authorities on engine manufacturers.

The effects of poor maintenance on exhaust emissions have been recognised for over 40 years (Holz 1960). However it was Waytulonis (1985) who demonstrated how a restriction in the air intake of 13 kPa and overfueling by 20% could result in an increase in particulate generation of 1038%.

While such a severe inlet restriction coupled with a massive degree of overfueling is likely to be rare, he did conclude that the single faults that increase particulates were intake restriction (+44 to +164%) and overfueling (+125% to +173%). A key factor that was also identified was that in the absence of severe faults or mal-adjustments, exhaust emission quality did not degrade excessively during the initial 4,000 hours in service.

After this time engines typically developed the following trends; carbon monoxide increased, hydrocarbons increased, oxides of nitrogen decreased and particulates increased. Waytulonis (1985) examined a total of 13 engines from five US mines, however only mines with a perceived good maintenance record were willing to supply engines for assessment. The lack of engines from mines with lesser developed maintenance programmes may have resulted in Waytulonis under-stating the effects of maintenance on diesel particulate control.

Recently Davies (2000) explored the effect of maintenance on diesel particulate emissions on one engine in the NSW coal industry. In this case an engine was measured for total carbon in the raw exhaust and a value of 0.84-1.4 g/kWhr recorded.

The inlet flame trap was removed and cleaned in an ultrasonic bath for approximately 15 minutes, dried, replaced and the exhaust re-measured under the same load conditions. The total carbon was reduced to 0.38-0.40 g/kWhr, a reduction of 55-71%.

The practice of de-rating engines to reduce emissions (Schnakenberg and Bugarski 2002) does not find favour within the Australian coal mining industry. The practice adopted in the USA occurs almost exclusively at mines located at high altitudes (12,000 feet) and does not appear to be common at more conventionally located mines.

Discussion with one Australian OEM resulted in the statement that he had never de-rated an engine and never would as best performance was achieved at maximum power (Berriman 2002). In the opinion of this OEM it was more appropriate to rate the engine to the task it was required to perform rather than de-rating.

Recently MSHA (2003) has published guidance on the maintenance of diesel equipment used in underground coal mines to minimise diesel particulate generation. Recommended actions include checking for:

- Clogged air filters and leaks in the air intake system.
- Correct fuel injection rate.
- Correct fuel injection timing.
- Correct operation of all fuel injection system components (fuel filters, water separators, fuel pumps and fuel injectors).
- Correct operation of electronic engine controls.
- High oil consumption.
- Increased carbon monoxide emissions.
- Clogged DDEFs

Under NSW legislation many of these issues are normally checked under routine maintenance programmes.

2.8 SUMMARY

Diesel particulate has been found to consist primarily of small particles (15 – 30 nm) which agglomerate together to form larger particles which are typically less than 1 μm in diameter. Such particles are in the respirable size range and thus can be transported to the alveoli. The chemical composition is essentially a carbonaceous nuclei surrounded by organic matter with traces of inorganic compounds.

The potential for such fine particles to give rise to adverse health effects in the occupational situation has been the subject of intense scientific debate for the past 25 years.

Even to this day no definitive dose response relationship has been established. Recently a number of independent statistical analyses of the epidemiologic literature have concluded that a causal association between increased risk of lung cancer and exposure to diesel exhaust exists, however these types of studies are the subject of criticism by some sectors of the scientific community.

Some authorities, including the NSW Joint Coal Board (1999) have suggested a potency at the risk level associated with passive cigarette smoke.

Methods for the quantification of employee exposure to diesel particulate have been under development for approximately 30 years, with elemental carbon gradually evolving as the analyte of common choice. Numerous issues have arisen with the use of this analyte in coal mines due to possible interferences from the host material being mined but these appear to be moving to a degree of resolution.

Considerable research has been undertaken in the area of control technologies, however the early focus was almost exclusively on fuel quality.

Since 1988 techniques such as disposable exhaust filters, engine decoking, etc have been examined, with excellent results in the control of diesel particulate. Little research appears to exist in regard to the standardised testing of disposable exhaust filters, and the potential for significant improvements as a result of the implementation of specific maintenance criteria (first identified in 1985) appears to have gone largely unresearched, especially in the underground coal mining industry.

It is proposed that these two areas will be examined in greater detail and form the basis for the majority of this research project.

3. RAW EXHAUST DIESEL PARTICULATE MEASUREMENT SYSTEM

3.1 INTRODUCTION

For in excess of 30 years, one of the key control measures for gaseous emissions in the NSW underground coal industry has been the statutory requirement for routine raw exhaust gas tests every six months.

Initially samples were collected in glass gas bottles and analysed in a laboratory by wet chemical methods. From the mid 1970's, mobile laboratories containing infrared and chemiluminescence analysers have been used. This approach has been very effective in identifying those engines that generate excessive gas concentrations and thus increase employee exposure.

The approach to raw exhaust particulate monitoring has been less rigorous. The Australian underground coal mining industry has relied on the Bosch Smoke Meter (based on the visual comparison of a known volume of exhaust drawn through a filter) as the sole means of measuring soot levels in the exhaust of diesel engines.

These measurements were normally made during the approval of an engine package and no further routine monitoring was performed. Daniel (1998) conducted considerable research on the Bosch Smoke Meter and concluded that it was not useful at low load conditions. MSHA (1996) overcomes these difficulties via the use of dynamometers, dilution tunnels and gravimetric analysis. Davies (2000) suggested the use of a measurement system (Rupprecht & Patashnick Co Inc Series 5100 Diesel Particulate Measurement System) based on the collection of particulates in the exhaust and their subsequent analysis for organic, elemental and total carbon.

This approach has significant merit as it measures the parameter of prime health concern, elemental carbon (Mauderly 1992, Heinrich et al 1995) and thus it was considered appropriate to use this instrument in the current research project. Davies (2000) had also highlighted a number of operational issues with the Series 5100 analyser that required resolution prior to routine use.

Prior to the commencement of field work it was also necessary to miniaturise the instrument and sampling train, previously used by Davies (2000), by installing it inside a custom-built trailer suitable for transport to mines owned by BHP Billiton Illawarra Coal.

3.2 RUPPRECHT & PATASHNICK CO INC SERIES 5100 DIESEL PARTICULATE MEASUREMENT SYSTEM

3.2.1 Principle of Operation

The instrument operating manual (Rupprecht & Patashnick, 1996) describes the Series 5100 analyser as employing a direct measurement approach to determine the concentration of carbon in diluted or raw diesel exhaust.

A vacuum pump draws a sample of raw exhaust through a heated probe that has been placed in the exhaust stream. The incoming particulate laden gas stream travels through a specialised switching valve to a quartz filter, where the particles are trapped (Figure 3.1).

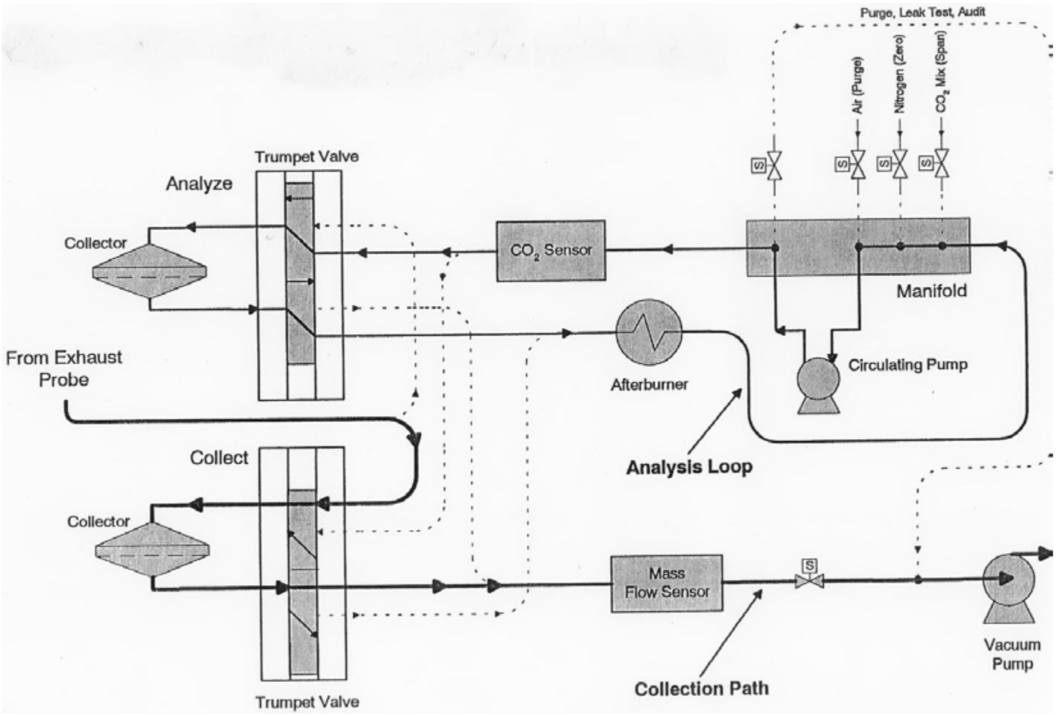


Figure 3.1
Diesel Particulate Analyser

Four quartz iodide lamps located around the filter are used to ramp the filter temperature up and oxidation converts the carbon-based materials to carbon dioxide. An afterburner (750°C) oxidises any volatiles not burned on the filter. The concentration of CO_2 in the analysis loop is analysed by an infra-red based CO_2 meter and the concentration of carbon reported in mg/m^3 (based on the sample volume collected). While analysis is underway, another sample can be collected on a second quartz filter ready for analysis when the system becomes available. Up to four intermediate temperature ramps can be pre-programmed between 50°C and 750°C.

For the work reported, the system was configured in the default mode, ie 350°C (organic carbon) and 750°C (total carbon) with elemental carbon being obtained by subtraction. Calibration of the system is achieved by using standard concentrations of CO_2 in nitrogen.

3.2.2 Application to the Coal Industry

As previously discussed, Davies (2000) undertook an Australian Coal Association Research Programme project to establish the suitability of the instrument for the analysis of diesel particulate in the raw exhaust of underground diesel vehicles.

This research concluded that the Series 5100 diesel particulate analyser had the potential to provide a new tool to mine engineers to control the output of particulate from diesel vehicles. Davies (2000) also concluded that routine exhaust monitoring via mobile laboratories, similar to that used for gas analysis, may be particularly effective in controlling worker exposures.

Davies (2000) also provided an overview of diesel particulate emissions that could be expected to occur with engines used in the underground mining industry (Table 3.1).

Table 3.1
Range Of Exhaust Emission From Mine Vehicles

Engine Type	No. of Tests	Organic Carbon mg/m³	Elemental Carbon mg/m³	Total Carbon mg/m³	Total Carbon Output g/kWhr
Caterpillar 3304	100	3.6 – 49	26 – 217	33 – 224	0.14 – 1.3
Caterpillar 3306	73	3.9 – 70	15 – 158	34 – 181	0.13 – 0.90
Caterpillar 3306 Turbo	10	10 – 36	38 – 62	58 – 75	0.06 – 0.27
Hino	17	13 – 66	31 – 58	54 – 115	0.09 – 1.0
KIA 6-427	77	3.4 – 70	56 – 234	66 – 250	0.33 – 1.7
MWM D916	21	3.7 – 31	72 – 176	96 – 183	0.67 - 1.0
Perkins 1006.6	25	4.0 – 29	39 – 101	51 – 118	0.25 – 0.44

Further examination revealed significant variations within the same engine type (Table 3.2) which suggested that external factors must be influencing the results, as all engines of the one type should produce a similar exhaust profile.

Table 3.2
Results From Various PJB Vehicles

Engine Type	Vehicle No.	Organic Carbon mg/m^3	Elemental Carbon mg/m^3	Total Carbon mg/m^3	Total Carbon Output g/kWhr
KIA	PJB 98	4.8 – 23	72 – 125	84 – 139	0.47 – 0.88
KIA	PJB 102	5.8 – 31	96 – 159	103 – 181	0.36 – 1.1
KIA	PJB 107	9.4 – 26	169 – 199	180 – 223	1.0 – 1.5
KIA	PJB 108	3.4 – 70	56 – 224	66 – 245	0.33 – 1.2
KIA	PJB 115	7.0 – 33	147 – 209	160 – 242	0.84 – 1.4
KIA	PJB 116	8.8 – 26	116 – 177	141 – 191	0.83 - 1.1
KIA	PJB 132	9.3 – 34	178 – 223	202 – 241	1.3 – 1.6
KIA	PJB 7068	11 – 36	143 – 234	176 – 250	1.3 – 1.7

Further investigation on one engine (PJB 115) indicated simple maintenance practices such as cleaning the intake flame trap in an ultrasonic bath, had a dramatic effect on exhaust emissions (Table 3.3).

Table 3.3
Results of PJB 115 Pre and Post Maintenance

	Organic Carbon mg/m^3	Elemental Carbon mg/m^3	Total Carbon mg/m^3	Total Carbon Output g/kWhr
Prior to Maintenance	7.0 – 33	147 – 209	160 – 242	0.84 – 1.4
Post Maintenance	4.6 – 14	59 – 70	70 – 75	0.38 – 0.40

From this work it is clear that the Series 5100 diesel particulate analyser offers significant benefits over the Bosch Smoke Meter in the Australian underground coal mining industry.

3.2.3 Design of the Mobile Laboratory

In order to make the Series 5100 measurement system capable of achieving the goals of the current research project, it was necessary to completely dismantle the system used by Davies (2000) and reconfigure the system on a much more compact basis within a mobile trailer.

To this end, a design was developed and the trailer constructed around the measurement system. Care was exercised to ensure that the height of the trailer was such that it could be transported underground, construction was rugged and that all statutory requirements were observed. At the conclusion of the exercise the system was compact, capable of being operated by one person and capable of being easily transported to any mine. Figures 3.2 – 3.4 provide an overview of the layout of the instrument and associated sampling train and calibration equipment.

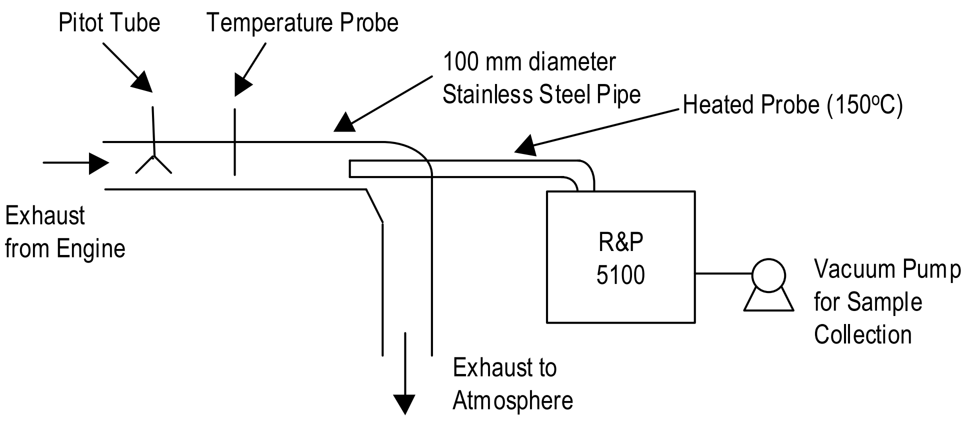


Figure 3.2
Schematic Diagram of R&P 5100 Sampling System

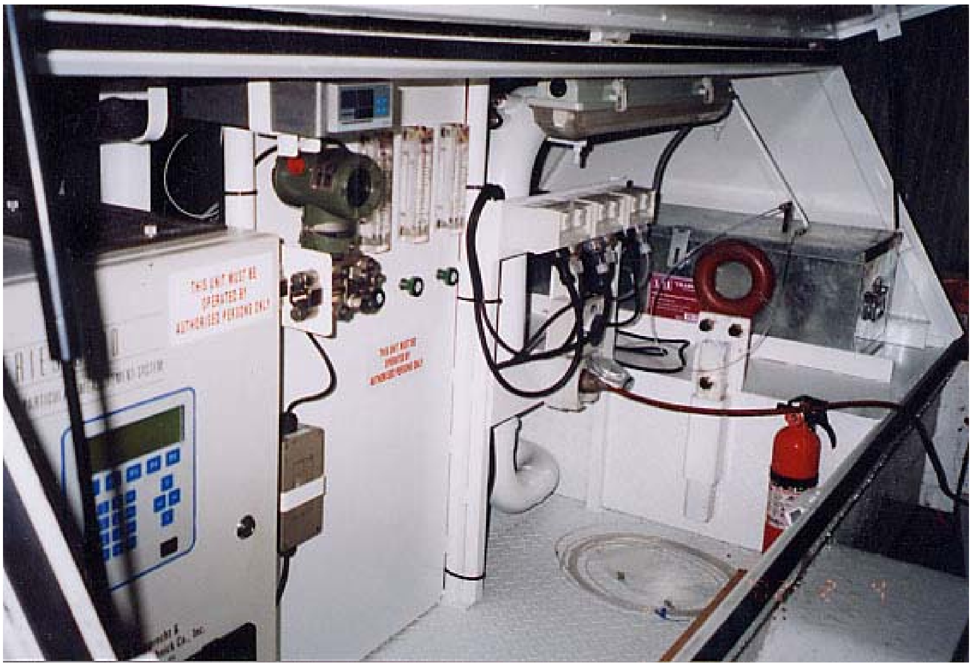


Figure 3.3
Photograph of R&P Series 5100 Analyser

Figure 3.4
Photograph of Mobile Collection & Analysis System

3.2.4 Factors Influencing Sample Collection and Analysis

During the course of the development of the mobile system a number of issues arose which required consideration.

Considerable water vapour carryover from the water-filled scrubber tanks was experienced which resulted in water condensation in the mass flow controller. This problem was traced to the size of the water trap being insufficient to condense out all water vapour prior to entry into the mass flow controller. A large water trap was supplied by Rupprecht & Patashnick Co Inc which minimised the problem so that a day's sampling could be undertaken before it was necessary to shut down the system to drain the trap.

This condition was not experienced by Davies (2000) and further investigation indicated that he used a sampling time of 30 seconds compared to 60 seconds used in the current exercise. Also, the current design aimed to minimise the distances between the engine and the R&P Series 5100 analyser which was not the case in the setup previously used in the ACARP research (Davies 2000).

The other limiting factor of the sampling and analysis system was the fact that it was not intrinsically safe for entry into coal mines, as per the requirements of the NSW Department of Mineral Resources.

To undertake such a task was assessed to be very expensive and unwarranted, given that site approvals could be obtained for the unit to operate in restricted areas (workshops) of the mine. This effectively limited the number of engines at a mine that could be tested as they would have to be driven to the workshop for testing and operational conditions would not always allow such a practice.

To minimise impact on operations, testing was conducted whenever possible on vehicles that had come to the surface for specific maintenance requirements. This still allowed for a reasonable cross section of vehicles to be evaluated but not the total fleet as was originally anticipated.

Access to vehicles was also affected as a result of the closure of Tower Colliery on 20 December 2002. A number of older vehicles were retired from service while others were upgraded prior to transfer to another operation within BHP Billiton Illawarra Coal.

3.3 CALIBRATION AND VALIDATION OF MEASUREMENT SYSTEM

3.3.1 Calibration Procedures

The various components of the measurement system used in this project were calibrated in the following manner.

3.3.1.1 *Rupprecht & Patashnick Inc Series 5100 Diesel Particulate Analyser*

As per the manufacturer's recommendations the instrument was calibrated using National Association of Testing Authorities (NATA) certified standard gas mixtures of carbon dioxide in nitrogen.

Nitrogen was used as the zero standard. A NATA approved laboratory rechecked all cylinders at regular intervals to ensure that they had not altered their composition.

3.3.1.2 *Temperature Sensor*

The temperature sensor was calibrated against a reference thermocouple over a range of temperatures and found to be within the requirements specified by NATA (2000).

3.3.1.3 *Flow Meter*

The pitot tube flow meter system was calibrated by passing air through the system at varying flow rates and compared against a standard inclined manometer. The results from the pitot tube were graphed against those of the inclined manometer and an equation for the line of best fit obtained. All pitot tube readings taken during the project were corrected back to those of the standard inclined manometer using this equation.

Temperature and flow rate measurements were only required when results were converted to g/kWhr. All results from the instrument were in mg/m^3 at standard temperature and pressure (STP). The instrument was programmed to measure all internal flows and temperatures and make the appropriate conversions so that the results were reported at STP.

3.3.2 Validation Procedures

3.3.2.1 *Manufacturer*

Validation of the Series 5100 Diesel Particulate Analyser under operating conditions does not appear to have been performed in substantial detail by the manufacturer. Okrent (1996) does report on tests performed on a single engine at steady state conditions. Comparison to the US EPA filter method (gravimetric) was reasonable, however the level of elemental carbon present in the exhaust was only about 9 mg/m^3.

Okrent (1996) did demonstrate that the analyser would not indicate the presence of any elemental carbon when none was present by sampling volatilised oil. All the oil was released by the filter at 350°C thus recording its presence as organic carbon. No further carbon was detected at 750°C.

3.3.2.2 *Other Researchers*

Weller et al (1999) used the Series 5100 analyser in studies on particulate composition when using vegetable oil lubricant in a diesel engine. Weller et al (1999) indicates that the Series 5100 gave results consistent with other techniques used previously by the other researchers (Asadauskas, Perewz and Duda 1996). The researchers also noted that the Series 5100 analyser consistently yielded a higher volatile fraction as a percentage of total particulate mass than solvent extraction techniques. Several factors as to this difference are discussed with a cautious note being exercised about direct comparisons of techniques.

Davies (2000) undertook extensive validation tests as part of an ACARP project. Comparisons were made to samples collected on quartz filters and analysed by NIOSH Method 5040 (NIOSH 1994). Comparisons were also made between the Series 5100 and gravimetric analysis for diesel particulate.

A reasonable relationship (R^2 = 0.77 and 0.82 for the two data sets) was found between elemental carbon measurements, however the relationship between total carbon and gravimetric analysis of diesel particulate (R^2 = 0.66) was less precise. Davies (2000) attributed this second situation to the small sample volumes involved, resulting in small weight differences and potentially significant errors.

Caution needs to be exercised when comparing data either collected or analysed by different methods. For example the definition when measuring elemental carbon with the Series 5100 is merely based on temperature (ie below 350°C is assumed to be organic carbon and the fraction between 350 – 750°C is assumed to be elemental carbon).

On the other hand NIOSH Method 5040 flushes the organic carbon from a collected sample by heating it to 700°C in an inert helium atmosphere. The furnace is then cooled to 25°C and a 2% oxygen mixture is introduced to oxidise the elemental carbon (at a temperature of 850°C) so the resultant carbon dioxide can be flushed out and catalytically converted to methane prior to entry to the measurement system.

Clearly these differing analytical approaches, together with different collection procedures, give rise to errors, the full extent of which remains unknown.

3.3.3 Australian Validation Trials

3.3.3.1 Introduction

Prior to April 2003 suitable test facilities did not exist within Australia to conduct more extensive validation trials than those previously reported in sections 3.3.2.1 and 3.3.2.2. However, as part of a project (conducted by the NSW Department of Mineral Resources (DMR) and funded by the Joint Coal Board Health & Safety Trust) to identify suitable surrogate hand-held instruments to monitor raw exhaust diesel particulate, the opportunity arose for a further validation exercise.

In the DMR project a series of hand-held analysers were used to sample the raw exhaust of three engines (Caterpillar 3306, 3126 and KIA) on an engine dynamometer which had been integrated to a full-flow dilution tunnel.

The attraction of the project in regard to the Series 5100 Diesel Particulate Analyser was that one instrument to be tested was a Diesel Particulate Dosimeter being developed by NIOSH at the Pittsburgh Research Laboratory in Pittsburgh, USA.

This device (Volkwein 2001) measures the differential pressure across a filter as the diesel particulate mass loading increases. The filters are analysed by NIOSH Method 5040 (NIOSH 1994) and the elemental carbon concentrations used for calibration of the dosimeter.

The engines selected by the DMR for the project represented the most common engines in service at NSW underground coal mines (Caterpillar 3306 and KIA) and a new type of engine reputed to be a replacement for the older Caterpillar 3306 which is no longer produced.

All testing was performed at the NSW WorkCover TestSafe facility at Londonderry NSW. A manifold was constructed to allow simultaneous sampling of the surrogate instruments and Series 5100 analyser. Unfortunately, the NIOSH dosimeter could not be used at the same time and samples were collected after testing for the other instruments had been completed.

Notwithstanding the difference in sample timing, this project represented the best opportunity in Australia for further validation of the Series 5100 Diesel Particulate Analyser and thus it was considered worthwhile participating in the project.

3.3.3.2 *Test Procedure*

The DMR project committee developed the following test procedure.

1. Start the dilution tunnel (before operating the engine).

2. Start and warm up the engine.

3. Determine power curve.

4. Using opacimeter, determine under what condition the engine produces high levels of DPM, and what level of intake restriction (if any) is needed to get sufficiently high readings. Record these conditions, and the intake restriction.

5. Find operating conditions which give a good range of opacity from the maximum down. Record these conditions.

6. Set the first operating condition.

7. Monitor RPM, torque, CO_2, NO_x and opacity for stable readings.

8. When conditions are stable, inform the instrument operators that they can take readings:
   - EC analyser will take two samples and proceed with their analysis
   - Instrument testers will measure with each of three instruments for one minute, using the mini-dilutor
   - Tunnel operator will collect two pairs of filters at high loadings, and one pair of filters at light loadings (based on the time it takes, and availability of filters)
9. While measurements are being made, observe outputs for stability.

10. When instrument and tunnel measurements are complete, request NIOSH representative to use the NIOSH dosimeter to take Δp measurements via an open port in the sampling pipe.

11. When finished re-seal the port and inform the dyno operator.

12. The dyno operator will adjust the engine to the next conditions.

Repeat from item 6 above.

As the Caterpillar 3126 engine is fitted with a turbo charger it was considered necessary to include a transient test which would evaluate the contribution of the turbo charger. This is as follows.

1. Run engine to achieve normal operating temperature.

2. Before testing, accelerate engine to governed speed, (say) twice. This is to clear the cylinders of any accumulated oil, fuel, etc.

3. Engage high gear, and apply brakes, as for a torque stall test.

4. Start test: (time 0)

5. Idle for 30 seconds

6. At 30 seconds, open throttle fully and quickly; engine accelerates to torque stall speed

7. At 45 seconds, release throttle fully and quickly; engine decelerates, but not right down to idle.

8. At 55 sec, open throttle fully and quickly; engine accelerates again to torque stall speed.

9. At 90 seconds, release throttle fully and quickly; engine decelerates to idle speed.

10. At 120 seconds, finish test.

A graphical representation of this test is provided in Figure 3.5.

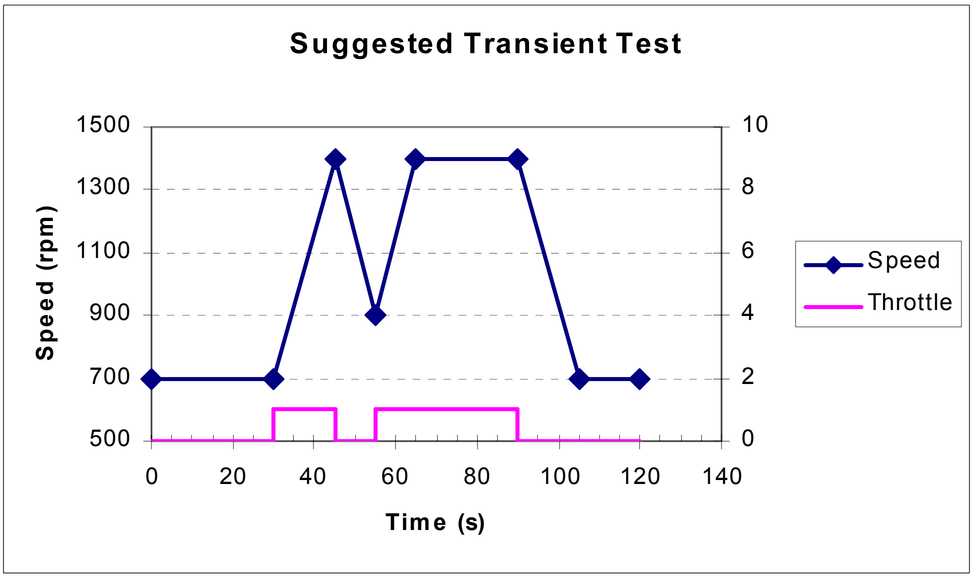


Figure 3.5
Graphical Representation of Transient Test

Testing took place with each engine configured as it would be in the field, namely fitted with an exhaust water conditioning bath. One engine (Caterpillar 3306) was also tested without an exhaust water bath but after testing it was discovered that a crack had developed in the dilution tunnel, thus affecting results. This work was later repeated but is not considered relevant as no engines in NSW mines are currently permitted to operate without a water conditioning bath or suitable heat exchanger and flame trap.

3.3.3.3 *Test Results*

The results of elemental and total carbon tests are listed in Table 3.4.

Table 3.4
Comparison of Series 5100 Analyser Vs NIOSH Dosimeter

Engine	RPM	Torque 5100 (5040)	Series 5100 DP Analyser		5040 Analyser of Dosimeter Filter	
			EC mg/m³	TC mg/m³	EC mg/m³	TC mg/m³
3306	1500	458 (458)	58	80	72	104
	1500	454 (455)	51	68	75	110
	1500	446 (450)	49	65	73	110
	1500	437 (440)	44	59	60	97
	1500	410 (410)	28	40	29	62
	1500	380 (380)	18	27	18	54
	Transient	Transient	17	30	24	56
KIA	2150	163 (166)	52	72	48	84
	2150	158 (157)	53	83	51	86
	2150	150 (150)	38	56	38	72
	2150	140 (142)	30	41	38	72
	2150	125 (125)	22	33	27	63
	2150	100 (100)	23	34	34	73
	2150	0 (0)	16	26	22	65
	Transient	Transient	23	37	20	42
3126	2100	600 (628)	45	65	17	53
		588 (585)	37	81	26	71
		565 (575)	52	88	22	61
		565 (564)	50	87	24	79
		540 (540)	53	84	19	58
		515 (515)	45	65	29	66
		0 (0)	13	19	10	42
	Transient	Transient	26	39	12	35

In the results reported above, only the average result at each torque setting has been recorded. In the case of the Series 5100 analyser this was the average of two samples and three for the NIOSH dosimeter.

Examination of the data indicates a good relationship for elemental carbon on both the Caterpillar 3306 and KIA engines (R^2 = 0.95 and 0.87 respectively). The relationship for elemental carbon on the Caterpillar 3126 engine was much less precise (R^2 = 0.43).

The relationship between techniques for total carbon was less precise than the elemental carbon for all engines (R^2 = 0.84, 0.49 and 0.65 for Caterpillar 3306, KIA and Caterpillar 3126 respectively). An examination of the graphical plots of data points for the KIA engines suggested that the transient results were abnormally influencing the overall correlation. Removal of this datapoint resulted in a revised R^2 for the KIA engine (total carbon) of 0.85. For comparison, the transient data point for both the Caterpillar 3306 and 3126 were also removed and the data re-analysed. This resulted in revised R^2 values of 0.82 for the Caterpillar 3306 engine and 0.58 for the 3126 engine.

To see if a similar situation occurred with the elemental carbon results, the transient values were removed from the data for all three engines and the regression analysis repeated. This resulted in R^2 values of 0.96, 0.92 and 0.36 for the 3306, KIA and 3126 engines, respectively. Comparison to the data, which included the transient elemental carbon data, indicated a slight improvement in the correlations for the Caterpillar 3306 and KIA engine, with a slight degradation in the correlation for the Caterpillar 3126 engine.

As the focus of this project was to use the Series 5100 Diesel Particulate Analyser and the resultant ability to directly measure elemental carbon in the raw exhaust, the results in Table 3.4 are encouraging.

The comparison between the Series 5100 and the NIOSH Method 5040 analysis of filters from the NIOSH Dosimeter are good for both elemental and total carbon on the Caterpillar 3306 and KIA engines.

This is especially encouraging as these two engine types currently represent 68% of the NSW underground coal mine diesel fleet (NSW Department of Mineral Resources 2001).

The elemental carbon comparison for the Caterpillar 3126 engine was not consistent with the other two engines tested. Some possible reasons for this abnormality are:

- Due to the higher volume of the Caterpillar 3126 engine exhaust (resulting from the turbocharger) samples for the NIOSH Dosimeter could not be taken in exactly the same position as the previous two engines. A short extension was placed on the sample port inlet used for the other two engines. This resulted in the exhaust making a 90° turn prior to sampling as against the 5100 which was collected in the raw exhaust stream.

- The Caterpillar 3126 engine may be producing a greater number of smaller particles (nano particles) than the other two engines, which are not collected efficiently by the quartz filters used by the NIOSH Dosimeter. No data is available to support this theory.

- The high velocity of exhaust from this engine may be influencing the pressure sensor in the small sampling pump and thus under-sampling. Subsequent investigations on other high velocity engines indicated a similar problem with the NIOSH Dosimeter (Volkwein 2003) suggesting an instrumentation issue.

Notwithstanding the abnormality with the Caterpillar 3126 engine the good agreement on the Caterpillar 3306 and KIA engines (which represent the majority of the current diesel fleet) supports other validation attempts.

Caution should however be exercised when using the Series 5100 Diesel Particulate Analyser or the NIOSH Dosimeter on new generation turbo-charged engines until the reasons for the poor correlation of elemental carbon results are fully understood.

3.4 CONCLUSIONS

The measurement of particulate in the raw exhaust of coal mine diesel engines has historically been restricted to major research facilities, which have dedicated dilution tunnels. Analysis has historically been by gravimetric means with resultant issues such as moisture and sensitivity.

In the Australian underground coal mining industry, reliance for the control of particulate emissions has been solely on the Bosch Smoke Meter, a device that has shown to be unreliable under some conditions (Daniel 1998).

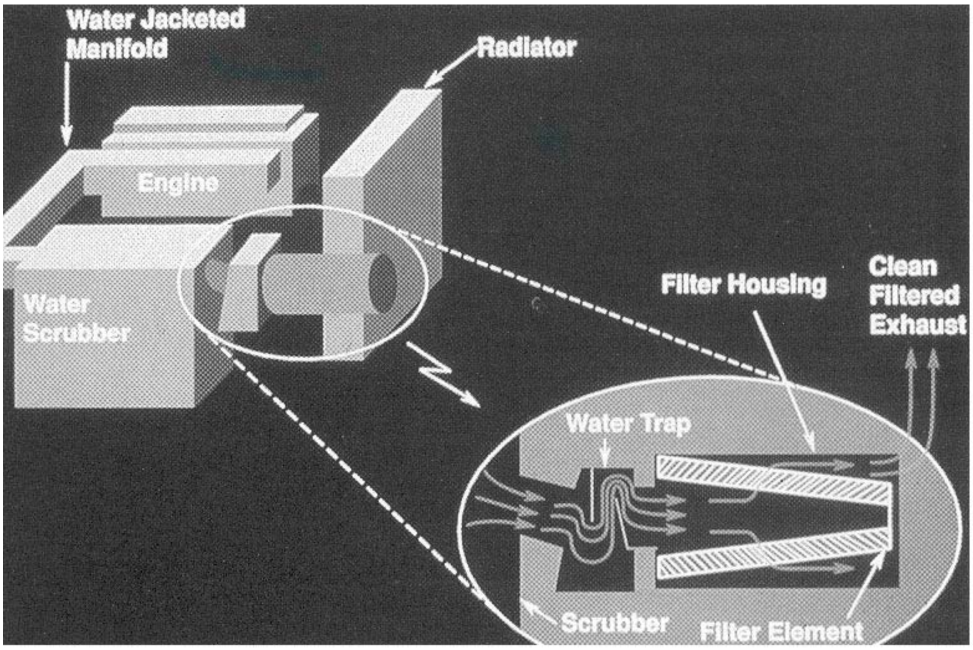
Given that the main contaminant of concern in regard to health issues and diesel particulate is elemental carbon, it was felt that any evaluation technique should be related to that parameter. The Rupprecht & Patashnick Co Inc Series 5100 analyser appears to meet that desire and validation testing, both within this project and by other researchers (Okrent 1996, Weller et al 1999, Asadauskas, Perewz and Duda 1996 and Davies 2000), indicates the instrument's suitability.

Care needs to be exercised however as validation of the Series 5100 instrument against NIOSH Method 5040 on a Caterpillar 3126 engine was not consistent with Caterpillar 3306 and KIA engines. As these last two engines make up 68% of the current NSW underground diesel fleet, and no Caterpillar 3126 engines are currently within the BHP Billiton Illawarra Coal fleet, the Series 5100 was considered the best option in this project to measure elemental carbon in the raw exhaust of operational engines.

4. DISPOSABLE EXHAUST FILTERS

4.1 INTRODUCTION

Disposable diesel exhaust filters (DDEF) were first proposed by the US Bureau of Mines (Ambs and Hillman 1992) as a means of controlling the level of DP being dispersed into the atmosphere from the exhaust of diesel engines operating in underground coal mines. The process involves the fitting of a canister to the exhaust system after the water filled conditioning tank, inserting a DDEF and operating the vehicle until the backpressure from the retained DP on the filter exceeds predetermined limits or some other operation parameter (number of hours in service). The process is illustrated in Figure 4.1



(Source: Donaldson Co Inc Bulletin #50-341)

Figure 4.1
Disposable Diesel Exhaust Filter System

All vehicles operating in the hazardous zone of Australian (and most overseas countries) underground coal mines are required by regulation to be fitted with a water-filled conditioning tank or an equivalent spark suppression system. In the case of a water-filled conditioning tank this serves a dual purpose in quenching any sparks that may arise from the combustion process and to cool the exhaust gases below the statutory limit of 150°C. In fact, due to the adiabatic cooling effect of the water, the exhaust gas temperature has a maximum value of approximately 77°C. The exhaust gas system from the engine block to the water-filled conditioning tank outlet is constructed in such a manner so as to be flameproof and any alteration to this design is governed by stringent statutory controls. Additions after the water-filled conditioning tank are either governed by OEM approvals or regulatory authority field approvals, which are much simpler to progress to an acceptable risk based outcome.

DDEF systems have been retrofitted to diesel equipment for over 10 years (Ambs and Hillman 1992) with scientific evaluation of their effectiveness being undertaken for a similar period (Ambs and Hillman 1992, Pratt et al 1993, Ambs et al 1994, Pratt et al 1995). While the results of this testing have demonstrated DDEFs as an effective means of controlling raw exhaust DP levels, the test methods have been different in application thus making direct comparison of results difficult. Considerable effort has been exhausted in sourcing appropriate filter media which have also been the subject of extensive evaluation (Ambs and Hillman 1992, Ambs et al 1994, Pratt et al 1995, Bickel and Taubert 1995).

From 1991, the approach in the USA has been to use low cost commercially available paper filter elements typically used as air cleaners on “over-the-road” diesel transportation vehicles. These low temperature filters were trialled in Australia (Pratt et al 1993) and rejected due to the potential for ignition if the water in the exhaust conditioning tank is lost.

As a result a non-flammable filter media was sourced (Pratt et al 1995) and following extensive testing has been developed into a commercial product known as the Microfresh DA100 filter. This system has been in use at some NSW underground coal mines since 1996.

4.2 AIM OF PROJECT

Historically, only one exhaust filter design has been developed within Australia (Pratt et al 1995) due to the lack of suitable filter media and the inability to easily evaluate potential filter media and pleating patterns in respect to filtration efficiency and backpressure. This has resulted in an industry reliance upon one design which uses imported filter media, the cost of which accounts for 60% of the materials costs of a filter.

The aim of the project was to develop a test procedure that can be used to quickly evaluate potentially new disposable filter designs for suitability in respect to filtration efficiency and backpressure. Once established, the test procedure was used to critically evaluate the current Microfresh DA100 filter design to establish the minimum number of pleats that gave the best filtration efficiency (or an acceptable value) with the minimum backpressure.

4.3 FILTER MEDIA

The original low temperature DDEF evaluated by Ambs and Hillman (1992) was constructed of cellulose filter media with a maximum recommended temperature limit of 100°C. The filter was produced by Donaldson Co Inc mainly for use in the over-the-road trucking industry as an air cleaner element.

Adaptation of this filter to mining equipment was originally undertaken by Dresser Industries Inc on a Jeffrey 4114 RAMCAR with in-mine trials being undertaken at a Utah Fuel Company mine. Ambs and Hillman (1992) indicated that the filter he used contained 270 pleats with a total surface area of 17 m^2.

An evaluation of the safety of this DDEF used on permissible mining equipment (that permitted to operate in hazardous zones of mines in the USA) found the following (Ambs and Setren 1995).

- Between 77 – 100°C no discernible difference in the concentrations of hydrocarbons, carbon monoxide and formaldehyde could be observed between the engine baseline emissions and post filter emissions.

- During ramp temperature tests the Donaldson filter showed an increase in hydrocarbon emissions at approximately 150°C indicating a breakdown in filter materials. Formaldehyde emissions remained relatively constant until 130°C whereupon the concentrations post the filter started to increase.

- A sharp increase in carbon monoxide occurred at 235°C indicating the ignition point of this type of filter media.

Ambs and Setren (1995) concluded that this type of filter media could be used “as exhaust filters on water scrubber type cooling systems used on permissible diesel-powered mining equipment with exhaust temperatures up to 77°C”.

Donaldson Co Inc in their bulletin No. 50-341 “Donaldson disposable diesel exhaust filter for coal mines”, claims that their product is 99%+ efficient in removing diesel particulate matter from the exhaust stream but qualifies this claim by stating that the US Bureau of Mines measurements were on average 95% ±4%.

The Donaldson filter has been used extensively since 1992 throughout the USA and is commonly called the Donaldson “cream” filter. In 2002 Donaldson introduced an upgraded product (blue filter) which is reputed to be more efficient than the cream filter in removing diesel particulate from the exhaust of an engine.

Other filter media have been evaluated over the years. Bickel and Taubert (1995) evaluated lava rock and woven fibreglass filter media with limited success. Lava rock was found to have a collection efficiency of 17% after the first hour of use, which to a maximum of 35 – 40% over a 28 hour test – well below that necessary for effective use in mining equipment. The woven fibreglass filters showed an excellent collection efficiency (greater than 85%), however as the filter became loaded the backpressure rose from 3.6 kPa in the clean state to 22.7 kPa with a loading of 58 grams. Given that the manufacturer’s recommended maximum backpressure for the MWM test engine was 11.2 kPa and this was exceeded within 30 minutes of operation, this material was not considered for further trials.

The other major filter media that has been used for DDEFs is based on polypropylene. This material, commercially manufactured by 3M Co Inc as “Filtrete”, was originally pleated by Microfresh Filters Pty Ltd and evaluated by BHP Steel Division Collieries (Pratt et al 1995). This material was chosen as an alternative to cellulose due to its low flammability characteristics and resistance to water. According to Microfresh Filters (Testing & Certification Australia, 2000), the product used in their filters is non-flammable at 960°C (using AS/NZS 4695 - 1996) and removes in excess of 89% of all diesel exhaust particulates in the 0.3 μm and above size range (Microfresh Filters 2002). Reference to the original material provided by Pratt et al (1995) indicates that the material melts at 170°C.

The Material Safety Data Sheet (MSDS) for Filtrete, provided by 3M Australia Pty Ltd (2002), indicates the product is non-hazardous according to the criteria of the National Occupational Health & Safety Commission, is composed of 100% polyolefins, and thermally decomposes (no decomposition temperature provided) to produce carbon monoxide, carbon dioxide, aldehydes, ketones and hydrocarbons.

Discussions with representatives of Microfresh Filters (Hinds and De Jersey 2002) indicated that the total surface area of the current DA100 filter (200 pleats) was 7 m^2. The original filter consisted of 220 pleats which was based upon the face area of the filter media required for the exhaust flow and the anticipated loading capacity of the filter. Based on the visual inspection of used filters the pleat numbers were reduced to 200.

While the majority of usage of this type of filter media has been in Australia, one original equipment manufacturer (Eimco) is marketing the product in the USA.

4.4 FILTER LIFE

As a general statement the filter life of a DDEF is determined by the exhaust backpressure it imposes upon the engine, the exhaust of which is being filtered. Ambs and Hillman (1992) indicated that a 112 kW engine fitted to a Jeffrey RAMCAR could be operated with a Donaldson DDEF for up to 10 hours before the backpressure on the engine exceeded 8.46 kPa (maximum manufacturer's recommendation). This value was made up of a 2.49 kPa contribution from the water bath and exhaust system and 5.97 kPa from the DDEF. Ambs and Hillman (1992) correctly points out that filter life on a water bath scrubber equipped vehicle is dependent on a number of factors such as: duty cycle, type of engine, engine condition and mine altitude.

It was also recognised by Ambs and Hillman (1992) that saturation of the filter by water carried over from the scrubber system was a prime cause of increased filter backpressure.

Discussions with USA based operators and an MSHA representative (Setren 2002) indicated a reluctance to exceed the maximum engine backpressure limits as this may result in the voiding of warranties.

The testing of Microfresh filters for filter life was first undertaken by Pratt et al (1995) in which it was found that 2-3 shifts' use could be obtained when the system was fitted to engines with ratings of 68 - 175 kW. Backpressures reported by Pratt et al (1995) were 3 kPa for no filter, 4 – 10 kPa for one shift use, 10 – 15 kPa for two shifts' use and 15 – 20 kPa for three shifts' use. While the backpressure without a filter was similar to that reported by Ambs and Hillman (1992), i.e. 2.49 kPa versus 3 kPa, the subsequent backpressures as the filter loaded were above that reported by Ambs and above that recommended by the Australian OEM for the vehicle being tested (i.e. 9.3 kPa) when the unit was operated for more than one shift with a single canister.

Notwithstanding the above results it was concluded that the Microfresh filter system offered the best overall choice of a system (considering issues such as flammability, etc) and thus the system was commercialised. Discussions with personnel at two BHP Billiton Illawarra Coal operations (Elouera and Appin Collieries) indicated that in the absence of any viable filter use indication system, the collieries had adopted a policy of changing filters each shift regardless of the number of hours in use. Such a policy results in excessive use of filters with a resultant increase in operating costs.

4.5 METHODOLOGY AND TECHNIQUES

4.5.1 Historical Test Methods

The first evaluations of DDEF efficiencies were conducted by the US Bureau of Mines (Ambs and Hillman 1992). These initial tests involved fitting three Jeffrey 4114 RAMCARS with DDEF exhaust control systems and operating the vehicles with and without filters for a total of seven production days. The reduction in DP in the mine environment was measured with size selective aerosol samplers followed by gravimetric analysis (Cantrell and Rubow 1992). The results of this trial are provided in Table 4.1.

Table 4.1
US Bureau of Mines Disposable Filter Efficiency Tests

Sample Site	With DDEF Installed mg/m³	Without DDEF Installed mg/m³	% Reduction[1]
Intake	0.06 ± 0.02	0.06 ± 0.02	N/A
Haulage	0.12 ± 0.02	0.50 ± 0.02	94 ± 6
Return	0.09 ± 0.03	0.80 ± 0.03	98 ± 4
Jeffrey Shuttle Car (RAMCAR)	0.17 ± 0.05	0.81 ± 0.03	93 ± 7

N/A – Not Applicable
[1]Corrected for ventilation and production change

The filters used in these tests were a low temperature paper filter media DDEF manufactured by Donaldson Co Inc. These devices had a maximum recommended operating temperature of 100°C, which is not normally an issue as the maximum possible gas temperature from a water-filled conditioning tank is 77°C.

Owing to the success of these trials a number of Donaldson DDEF were imported to Australia and testing undertaken in a surface test tunnel at Tower Colliery (BHP Steel Collieries 1993). The surface test tunnel was constructed of steel formwork and plastic sheeting (brattice) being approximately 50 m long, 5 m wide and 2.5 m high.

By the placement of an auxiliary exhaust fan at one end, ventilation flow rates could be controlled to statutory requirements for gaseous emissions. Testing conducted using similar techniques to Ambs and Hillman (1992) gave the results indicated in Table 4.2.

Table 4.2
BHP Steel Collieries Disposable Filter Tests

With Filter DP mg/m^3	Without Filter DP mg/m^3	% Reduction
0.24	1.1	78
0.14	0.72	81
0.17	0.91	81

From the results listed in Tables 4.1 & 4.2, it is evident that the % reduction in DP obtained by Ambs and Hillman (1992) is approximately 15% greater than those achieved by BHP Steel Collieries (1993).

Similar monitoring techniques have continued to be used, both in Australia and overseas, in order to establish the filtration efficiencies of various media.

A number of issues arise with this evaluation technique. First, the method is very long, requiring at least a two shift operation (ie one shift without a filter and another with a filter) in order to obtain a single result. This is very expensive and limits the ability to test new systems. Secondly, the test procedure relies on the gravimetric analysis of deposited DP. Weighing of this material introduces significant errors, especially with post filter samples, as the deposited mass is significantly less. The third issue is one of contamination. As all samples are collected in the general airbody of the mine, contamination from vehicles moving outbye of the test area is possible. Historically this has been accounted for via the means of an outbye sample which is then deducted from all other samples.

Experience has suggested that such procedures may be subject to external influence, for example thermal stratification of airways (Pratt et al 1995) potentially compounded the accuracy of the method in that it was impossible to account for such factors with such a limited sampling regime.

Discussions with a representative of an overseas regulatory authority (Setren 2002) indicated that in regard to DDEF used in the USA, reliance had been placed upon suppliers to provide information as to the filtration efficiency of individual filter media. It is understood (MSHA 2002) that this policy was in the process of review with both MSHA and NIOSH developing techniques to evaluate the efficiency of filters.

Discussions with one filter media manufacturer (Gorman 2002) indicated that they tested filter media in a similar manner to that used for respirators. The process involved taking a section of a filter pleat pack and testing it according to AS/NZS 1716 Appendix C (AS 1716-1994). A TSI type 8110 automated filter tester was used, with the device being calibrated annually against similar units in the USA. The test aerosol used was polydisperse particles of sodium chloride mainly within the size range of 0.02 – 2 μm equivalent diameter and a mass median diameter of approximately 0.3 - 0.6 μm. The challenge test aerosol concentration is in the range 5 - 15 mg/m^3 at a flow rate of 95 litres per minute.

Testing of SBMF40 filter media (that used in Microfresh DA100 DDEF) gave the following results (Table 4.3) using this process.

Table 4.3
Laboratory Test Results of Filter Media

Filter Media	% Efficiency	Pressure Differential mm H_2O
SBMF40	95	11.8

A number of issues arise with the process used by many manufacturers. Firstly, the media is glued to a metal holder thus ensuring a 100% seal. This may not always be the case in real life with some leakage around the filter possible (much is routinely done to ensure any such leakage is negligible).

Secondly, the test process does not involve the use of the contaminant of interest, with sodium chloride being used rather than diesel particulate. Moreover, diesel aerosol exhaust has been shown to have a mass median diameter of 0.15 μm (Cantrell 1992) as against that of 0.3 – 0.6 μm for the sodium chloride aerosol used in the TSI type 8110 filter tester. Two other factors are significantly different from the manufacturer's test procedure to that experienced under operational conditions. These are: the range of DP concentrations for engines used in coal mines is typically 33 - 250 mg/m^3 (as total carbon dependent on engine condition and load) as against a concentration of 5 - 15 mg/m^3 sodium chloride and the exhaust flow rate passing through a DDEF is approximately 660 litres/min as against 95 litres/min used in the manufacturer's test.

Given the factors indicated above, there is sufficient reason to believe that efficiency testing conducted in the manner typically used within Australia (and probably elsewhere given the lack of documented evidence to the contrary), would give rise to inflated efficiency values for DDEF.

4.5.2 Historical Filter Test Rig Designs

For decades filter designs have routinely been tested on laboratory facilities, however the evaluation process in regard to particulate filters for the mining industry is relatively recent. One of the most detailed reports of a test rig specifically constructed to evaluate diesel particulate traps (exhaust filters for over-the-road vehicles) was by the 3M company (Brunner 1995). When developing their system the 3M company determined the primary requirements of a suitable sampling system are that it should have:

- Mass-based measurements
- Ability to sample both sides of the trap simultaneously or in rapid succession
- Minimal time for efficiency test
- Excellent repeatability
- Good resolution
- Simplicity of use and maintenance
- Minimal cost and space investment
- Fluorocarbon (TFE) coated borosilicate glass filter media, and
- Ability to measure the volatile fraction of the particulate deposited on sample filters on a post-test basis

This resulted in the development of four systems which had the following characteristics (Table 4.4).

Table 4.4
Characteristics of Test Rigs Developed By 3M Co Inc

Characteristics / Systems	47 mm Raw Gas Sampling	90 mm Raw Gas Sampling	Partial Dilution	Smoke Sampling
Mass-based Measurement	Yes	Yes	Yes	No
Simultaneous Upstream/Downstream Sampling	Yes	Yes	No	Rapid Sequence
Minimal Time for Efficiency Test	Yes	Yes	No	Yes
Excellent Repeatability	No	Yes	Yes	Yes
Good Resolution	No	Yes	Yes	Yes
Simplicity of Use and Maintenance	No	Yes	Yes	Yes
Minimal Cost/Space Investment	Yes/Yes	Yes/Yes	No/Yes	No
TFE-coated Borosilicate Glass Sample Media	Yes	Yes	Yes	No
Ability to Measure Volatile Fraction	Yes	Yes	Yes	No

Operational experience with these four systems was varied, with the 47 mm raw gas sampling system being discontinued due to the following reasons:

- The small size of the sample tubing resulted in high particulate attenuation between the inlet of the sample probe and the filter holder.
- Unacceptable weighing errors were experienced, particularly on the downstream filter.
- The use of separate vacuum pumps, desiccant columns and gas clocks resulted in high variations in sample flow between upstream and downstream sample trains.
- High maintenance items such as the desiccant resulted in leaks frequently developing in the connecting tubing.
- Errors resulted from the manual operation of the system.

As reported by Brunner (1995), these faults were addressed in the 90 mm raw gas system subsequently constructed by the 3M company. Sample times were limited to two minutes which gave a deposit on the upstream filter of 7 – 15 mg, depending on the mass concentration of the particulate in the exhaust. One issue cited by Brunner (1995) was the difference in the volatile fraction (organic carbon) observed between the upstream and downstream filters. Brunner postulated that the common occurrence of the upstream filter always containing a lower volatile fraction than the downstream filter was due to:

- The upstream filter being at a higher temperature, allowing more of the volatile hydrocarbons to bake off during sampling.

- The upstream filter, which collects more particulate mass, develops a larger pressure drop and thereby increases the mass of hydrocarbons that are volatilised.

- The transport time between the two sample probes allows greater opportunity for particulates to adsorb hydrocarbons.

Brunner concluded that all of the above effects could be realised via conducting an efficiency test of the system (blank test) using a straight pipe in place of a particulate trap.

Such tests had indicated a negative efficiency of up to 10% which approached zero as the flowrate and gas temperature increased.

The third system developed by the 3M company was a partial flow dilution sampling system.

This system was operated in both gravimetric and real time formats by using a TEOM (Tapered Element Oscillating Microbalance) as the analysis technique. The use of the TEOM provides a means by which transient effects can be observed.

In recent years (Lomb 2002), partial flow systems to measure particulates have lost support in that they are critically dependent on the accurate measurement and control of operating parameters in order to give the desired dilutions. A full flow system depends on the operation of critical orifices (whose performance is consistent) and does not require the same level of calibration, measurement or control as a partial flow system. Major diesel research projects within the Australian transport sector (Anyon et al 2000) have focused on full flow systems for these reasons.

Over the past 20 years there have been many variations of the above approaches used to evaluate the performance of particulate traps for use on over-the-road diesel vehicles. In respect to the mining/tunnelling sector, several organisations have conducted the majority of research on diesel particulate traps using engines mounted on dynamometers. These are:

- Canada Centre for Mineral and Energy Technology (CANMET).
- Mines Safety and Health Administration (MSHA) Approval and Certification Centre at Triadelphia, West Virginia.
- Verminderung der Emissionen von Realmaschinen in Tunnelban (VERT), a Swiss joint project to curtail the emissions from engines at tunnel sites.

The first reported testing of diesel exhaust control technologies using dynamometer based systems was most probably undertaken by CANMET (Mogan and Dainty 1987) in which a prototype venturi scrubber system was evaluated.

Procedures were developed for the testing of exhaust treatment devices as part of the approval process for use in Canadian non-coal, non-gassy mines (CANMET 1995). These procedures involved isokinetically sampling the exhaust emissions followed by gravimetric analysis on 47 mm fibre of glass filters.

Since 1996 CANMET has been intimately involved in the Diesel Emission Evaluation Programme (DEEP), a joint venture of operators, labour, regulators, research agencies and OEMs. The DEEP programme has funded a number of major research projects of ceramic filter trap evaluation but given the very low number of underground coal mines in Canada there has been no research on DDEFs.

The test system used by MSHA was developed by the US Bureau of Mines (Anderson et al 1992) and involves the use of a partial flow dilution tunnel with the collection of diesel particulate matter on Teflon fluorocarbon polymer-coated glass fibre filters. Gases are also evaluated via direct reading instrumentation and a vapour phase sampler (XAD-2 resin) is installed downstream from the particulate filter.

MSHA (Ambs and Setren 1995) have used the above system to conduct a safety evaluation of DDEF, however the focus was on establishing the levels of emissions generated when the filters were subjected to temperatures above their operational range. No data appears to have been published by MSHA in regard to the efficiencies of DDEFs against diesel particulate. One reason for this is the system in Triadelphia is not fitted with an exhaust water conditioner system (a prerequisite for the use of DDEFs). During discussions at a mining diesel emissions conference in Canada during 2002, this aspect was confirmed (Setren 2002), however the use of a water conditioner was under investigation.

In August 2003 MSHA reported on the limited testing of filters (Stackpole 2003) where samples were collected using a Sierra Instruments particulate sampling system with collected samples being sent to NIOSH in Pittsburgh for diesel particulate matter, elemental and organic carbon analysis.

To date only a total of 50 filters have been tested with a comparison being made to a standard paper filter (Donaldson P530866). A filter was judged to have failed if:

1. An equivalence of 0.97 or greater is not achieved (equivalence = efficiency candidate filter divided by efficiency of Donaldson P530866).

2. Filter shows excessive backpressure.

3. Filter is physically damaged by exposure to exhaust stream.

Using the above criteria, the Microfresh DA101 filter (200 pleat filter in USA format) was judged to have an equivalence of 1.05, the equal highest of the filters tested.

Details of the procedure used by MSHA are not readily available, however the focus appears to be to find a range of filters that meets the MSHA “standard” filter rather than assessing the characteristics of individual filters.

The basis for choosing the MSHA “standard” filter also remains unclear at this stage, which limits the usefulness of this test protocol outside the USA.

VERT commenced the evaluation of particulate traps in 1993 (Mayer 1998) using a 105 kW construction site engine (or equivalent) on a test bed (dynamometer) using ISO 8178 (1996) as the test protocol. Emission measurements for particulate are evaluated gravimetrically and a transient “soot puff” test is performed using an opacimeter. Particle size distribution is also established.

Using the above criteria and the 105 kW reference engine, VERT recommends the following filtration efficiencies for particulate trap systems on construction engines (Table 4.5)

Table 4.5
VERT Filtration Efficiency Recommendations

Test	% EFFICIENCY	
	New	After 2,000 Hrs
Total Particulates (gravimetric using ISO 8178 @ 4 test points)	>80	>75
Elemental Carbon (coulometric)	>90	>85
Soot Puff during Free Acceleration (opacity)	<10	<10
Particulate Penetration in Size Range 10 – 500 nm	<5	<10

This recommendation was the first to propose an efficiency rating of the filter system under test against elemental carbon, yet few details are provided (Mayer 1998).

As was the case in Canada, VERT has focused on ceramic type filter traps and has not reported any testing of DDEFs.

4.5.3 Project Test Rig Design

Critical examination of the above historical approaches and consideration of the method by which DDEF are fitted to underground mining vehicles in Australia, resulted in the development of a unique filter test rig using elemental carbon as the evaluation parameter.

Previous research (Davies 2000) had demonstrated the usefulness of the Rupprecht & Patashnick Co Inc Series 5100 diesel particulate analyser in establishing the concentration of elemental carbon in the raw exhaust of a diesel engine.

As elemental carbon is the prime contaminant of concern in regard to adverse health outcome (Mauderly 1992, Heinrich et al 1995) it was considered paramount that any evaluation of DDEF in the Australian mining industry should use elemental carbon as the analyte.

The test rig concept was to use the exhaust of a vehicle that was part of a mine diesel fleet so as to reproduce exhaust characteristics of the type normally experienced from mine vehicles. This exhaust was then to be sampled prior to entering a filter canister, of the same approximate size as that normally fitted to vehicles that had been fitted with a test DDEF. Post analysis of the exhaust was also envisaged so that filtration efficiency could be calculated. A schematic representation of the test rig is provided in Figure 4.2.

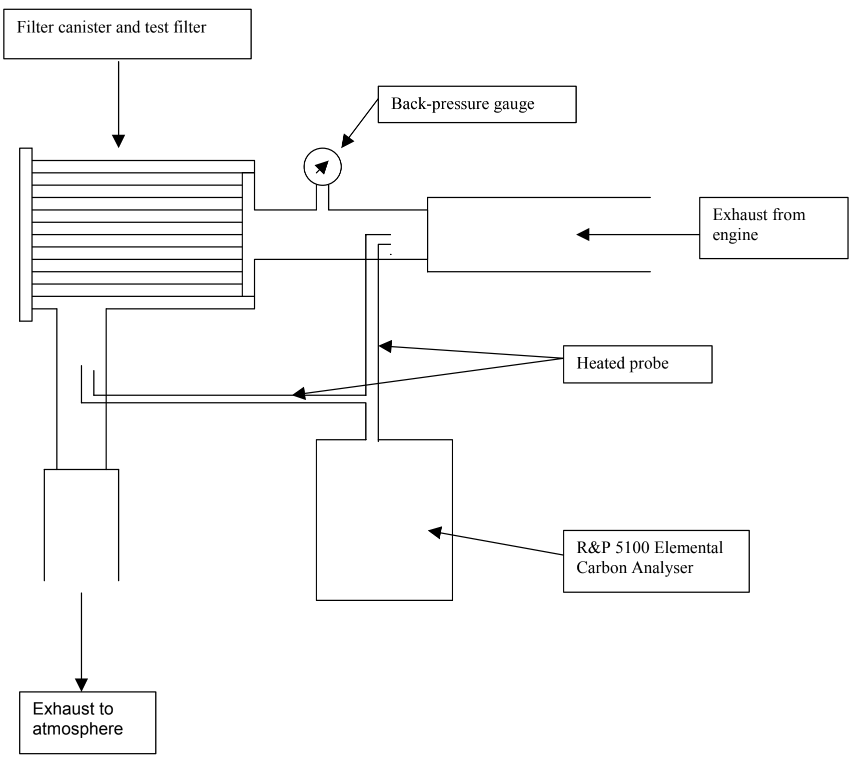


Figure 4.2
Diagram of Filter Test Rig Used in Project

Construction of the rig was in mild steel with the sections of piping where sampling was to occur being 100 mm in diameter. The dimensions of the canister were maintained as close as possible to those of systems currently fitted to vehicles.

As diesel particulate is known to be below 1 μm (Amman and Siegla 1982) isokenetic sampling was not considered necessary, however stainless steel heated probes were used for both pre and post sample collection. This approach is recommended in the Operating Manual (R&P 1996) supplied with the Series 5100 analyser.

A backpressure gauge was fitted between the entry to the DDEF and the engine, however initial trials indicated pressures to be so low that available instrumentation was not accurate. To address this situation a U tube manometer filled with water was connected in place of the pressure gauge.

The source engine for all testing was a 4 cylinder MWM D916.4 fitted to a Noyes Grader. Access to the raw exhaust (post the water filled scrubber tank) was obtained by removing the DDEF fitted to the vehicle and running a short section of flexible pipe from the grader to the inlet of the filter canister test assembly. A flexible pipe was also connected to the test rig post the filter canister so as to redirect the filtered exhaust (which contained significant concentrations of gaseous contaminants) away from the system operators.

Figures 4.3 – 4.6 provide a pictorial view of the process from exhaust generation by the grader, through the sampling system and canister to the Series 5100 analyser.

Figure 4.3
Photograph of Noyes Grader Used in Test Rig as Source of Particulate

Figure 4.4
Filter Test Rig with Heater Pre and Post Filter Sampling Probes

Figure 4.5
Changing Filter Element on Test Rig

Figure 4.6
R&P Series 5100 Diesel Particulate Analyser

Conditioning of the system was achieved by operating the grader for several days with no DDEF in the system. Pre and post samples were collected on several occasions and conditioning was considered complete when the pre and post elemental carbon results were approximately the same. This process provided an opportunity to establish the levels of elemental carbon likely to be produced by the MWM engine in the grader.

Based on these results the following operating parameters for the Series 5100 analyser were selected (Table 4.6) and used for all testing in the project.

Table 4.6
R&P Series 5100 Diesel Particulate Analyser
Sampling & Analysis Parameters

Sample Time	60 seconds
Pump Flow Rate	5 ℓ/min
Volume Sampled	5 litres
Heated Probe Temp	150°C
Filter Collection Temp	50°C
Initial Analysis Temp	350°C
Final Analysis Temp	750°C

Prior to every test the system was conditioned by performing one or more dummy test runs. All samples were collected with the engine either on high idle or under slight load (via hydraulics) so as to ensure that a suitable challenge concentration was achieved. In all cases a timed 60 second delay prior to sampling was observed to ensure the engine achieved a reasonable level of stability.

The following parameters were recorded:

Organic Carbon (OC)
Total Carbon (TC)
Elemental Carbon (EC)

The percentage filtration efficiency (F) was calculated from the following formula:

$$F (\%) = \frac{\text{Pre Filter EC (mg/m}^3\text{) - Post Filter EC (mg/m}^3\text{)}}{\text{Pre Filter EC (mg/m}^3\text{)}} \times \frac{100}{1}$$

4.5.4 Filter Backpressure Testing

Using the rig described in Section 4.5.3, all filters tested for filtration efficiency were monitored for backpressure. This usually involved taking a reading when the test engine was operating in its steady state condition on the first and the last efficiency test on each filter. This value essentially represented the no load baseline backpressure figure for each filter as the whole sampling process for each filter was in the order of 10 - 20 minutes.

To obtain a more representative backpressure assessment a number of filters were fitted to a Multi Purpose Vehicle (MPV). This vehicle was usually designated to transport materials into the mine (Elouera Colliery) on a specific duty cycle usually with a similar load each time. The hour meter fitted to the vehicle was used to record the number of hours the filter was in use each day and the efficiency was tested using the rig described in section 4.5.3 under the same test conditions each day. This process was repeated for a number of filters of different pleat numbers and where appropriate a plot of operating hours versus backpressure performed. All backpressures were measured in inches of water gauge and converted to kPa.

In order to limit variables, the same MPV and operator were used to conduct all operational backpressure testing. Due to an equipment breakdown a second but similar MPV was substituted on one occasion.

4.5.5 Number of Samples

As the basis of the research project was to evaluate and hopefully improve the only DDEF approved for use in Australia, only DA100 type filters from Microfresh Filters Pty Ltd were tested. No other filters suitable for testing could be identified.

The sampling programme for the project was designed on the basis that a selection of filters of varying pleat numbers would be analysed for filtration efficiency. Given that such an exercise has not previously been carried out, guidance was sought from Hawkins, Norwood and Rock (1991) as to the number of filters for each pleat number to be analysed. Hawkins, Norwood and Rock (1991) suggest a plateau is reached in estimating the mean and variance after about six to 10 samples. He suggests that more than 10 samples provide additional refinement in estimates but the marginal improvement is small considering that the cost per sample is essentially constant.

On the basis expressed by Hawkins, Norwood and Rock (1991) it was decided to conduct at least six (6) tests on a minimum of three (3) filters for each pleat size. Such an approach was considered adequate to provide sufficient statistical power and to overcome inter-filter variance.

A limited number of 170, 160 and 150 pleated filters, with a glue line holding the pleats apart, were tested for efficiency as part of a trial to see if such a process would improve the distribution of the filter load and thus reduce backpressure.

The list of filters and tests performed is provided in Table 4.7.

Table 4.7
Number of Filters Tested

Filter Type	No. of Pleats	No. of Filters Tested	Total No. of Tests
Microfresh DA100	200	10	29
	190	10	29
	180	9	28
	170	10	30
	160	7	22
	150	7	22
	140	3	9
	130	3	11
Microfresh DA100 with Internal Glue Line	170	3	11
	160	3	9
	150	4	14

4.5.6 Test Rig Blank Analysis

Throughout the duration of the testing programme a number of dummy sampling and analysis exercises were conducted on the test rig without any filters installed.

The process used on a normal test was observed in all details, with the results of each day's testing listed in Table 4.8.

Table 4.8
Test Rig Blank Values

Date of Test	Effective % Efficiency
24.11.02	+ 2.55
1.5.02	+ 3.29
13.5.02	+ 5.41
16.5.02	- 1.61
3.7.02	+ 1.85
2.8.02	+ 0.80
5.8.02	- 1.09
9.8.02	+ 1.77

Date of Test	Effective % Efficiency
12.8.02	+ 1.66
31.8.02	- 2.32
2.9.02	+ 7.44
30.9.02	+ 0.96
1.10.02	+ 5.55
8.11.02	+ 5.76
18.11.02	- 1.70
20.11.02	+ 8.32

These results are statistically described in Table 4.9.

Table 4.9
Statistical Summary of Test Rig Blank Results

Arithmetic Mean	=	2.738
95% Confidence Limits	=	0.952 – 4.523
Standard Deviation	=	3.47
Number of Tests	=	17

Based on these results all filtration efficiencies calculated in the test rig were reduced by 2.7% to take account of the elemental carbon losses within the system between the pre and post filter sample points.

Comparison of this result to the work of Brunner (1995) indicates that while the project test rig had a blank value of +2.7%, Brunner (1995) experienced a blank rig of zero to –10% in his 90 mm raw gas system, depending on flowrate and gas temperature. Given this, the test rig value of +2.7% would appear to be within experimental expectations.

4.6 EXPERIMENTAL RESULTS

4.6.1 Filtration Efficiency Versus Pleat Number

The results of filtration efficiencies performed on Microfresh Filters Pty Ltd DA100 disposable diesel exhaust filters (with varying pleat numbers) is listed in Table 4.10.

Table 4.10
Filtration Efficiencies of Microfresh DA100 Filters

Pleat Number	Filter Number	% Raw Filtration Efficiency	% Filtration Efficiency After Correction Test Rig Blank
200	1	78.7	76.0
		79.6	76.9
	2	84.5	81.8
		88.7	86.0
		88.7	86.0
	3	89.6	86.9
		87.0	84.3
		89.6	86.9

Pleat Number	Filter Number	% Raw Filtration Efficiency	% Filtration Efficiency After Correction Test Rig Blank
200	4	87.4	84.7
		84.5	81.8
		85.8	83.1
	5	87.2	84.5
		86.3	83.6
		88.3	85.6
	6	81.5	78.8
		74.6	71.9
		88.5	85.8
	7	84.5	81.8
		86.6	83.9
		85.4	82.7
	8	72.1	69.4
		84.0	81.3
		83.5	80.8
	9	88.1	85.4
		89.3	86.6
		88.4	85.7
	10	92.9	90.2
		91.7	89.0
		90.0	87.3
190	1	90.2	87.5
		93.3	90.6
		90.2	87.5
	2	92.1	89.4
		93.3	90.6
	3	92.4	89.7
		90.3	87.6
		88.1	85.4
	4	87.0	84.3
		89.9	87.2
		92.8	90.1
	5	85.0	82.3
		92.1	89.4
		93.3	90.6
	6	85.1	82.4
		80.0	77.3
		84.7	82.0
	7	86.6	83.9
		86.1	83.4
		85.3	82.6
	8	85.1	82.4
		87.2	84.5
		90.6	87.9
	9	82.2	79.5
		80.9	78.2
		77.0	74.3
	10	85.7	83.0
		83.9	81.2
		85.1	82.4

Pleat Number	Filter Number	% Raw Filtration Efficiency	% Filtration Efficiency After Correction Test Rig Blank
180	1	87.1 90.2 90.5	84.4 87.5 87.8
	2	90.1 89.2 93.3	87.4 86.5 90.6
	3	88.7 88.7 85.7	86.0 86.0 83.0
	4	91.1 88.7 88.4	88.4 86.0 85.7
	5	81.8 85.8 86.0 90.1	79.1 83.1 83.3 87.4
	6	89.3 88.1 90.8	86.6 85.4 88.1
	7	80.8 92.6 89.6	78.1 89.9 86.9
	8	89.2 88.1 88.7	86.5 85.4 86.0
	9	86.5 86.1 87.2	83.8 83.4 84.5
170	1	77.2 86.7 82.6	74.5 84.0 79.9
	2	83.0 87.1 83.2	80.3 84.4 80.5
	3	84.9 87.4 86.7	82.2 84.7 84.0
	4	85.3 76.4 90.5	82.6 73.7 87.8
	5	89.4 91.0 91.3	86.7 88.3 88.6
	6	91.9 92.2 91.6	89.2 89.5 88.9
	7	92.8 92.4 93.9	90.1 89.7 91.2
	8	92.1 94.1 94.3	89.4 91.4 91.6

Pleat Number	Filter Number	% Raw Filtration Efficiency	% Filtration Efficiency After Correction Test Rig Blank
170	9	93.6	90.9
		91.9	89.2
		91.4	88.7
	10	93.1	90.4
		92.2	89.5
		94.3	91.6
160	1	88.9	86.2
		89.2	86.5
		88.1	85.4
		88.1	85.4
	2	92.2	89.5
		86.4	83.7
		90.8	88.1
	3	87.2	84.5
		88.4	85.7
		89.1	86.4
	4	90.0	87.3
		85.6	82.9
		83.9	81.2
	5	83.9	81.2
		81.8	79.1
		81.0	78.3
	6	92.9	90.2
		91.7	89.0
		93.2	90.5
	7	92.5	89.8
		91.9	89.2
		93.3	90.6
150	1	89.0	86.3
		92.9	90.2
		88.5	85.8
	2	87.9	85.2
		74.6	71.9
		84.6	81.9
	3	90.9	88.2
		87.3	84.6
		83.5	80.8
		89.6	86.9
	4	80.4	77.7
		84.2	81.5
		82.4	79.7
	5	87.5	84.8
		86.5	83.8
		80.5	77.8
	6	85.9	83.2
		86.8	84.1
		91.1	88.4
	7	88.0	85.3
		93.1	90.4
		93.7	91.0
140	1	81.5	78.8
		83.6	80.9
		87.2	84.5

Pleat Number	Filter Number	% Raw Filtration Efficiency	% Filtration Efficiency After Correction Test Rig Blank
	2	90.7 90.4 86.1	88.0 87.7 83.4
	3	85.7 84.7 82.4	83.0 82.0 79.7
130	1	88.9 69.0 73.8 80.9	86.2 66.3 71.1 78.2
	2	90.7 90.4 72.2 85.1	88.0 87.7 69.5 82.4
	3	81.4 69.8 74.1	78.7 67.1 71.4

A limited number of tests were performed on filters with 170, 160 and 150 pleats plus an internal glue line to keep the pleats apart. It was considered that such an approach would improve the filter load distribution and thus reduce the filter backpressure. The results of efficiency tests on these filters are listed in Table 4.11.

Table 4.11
Filtration Efficiency of Filters with Internal Glue Line

Pleat Number	Filter Number	% Efficiency	% Efficiency After Correction For Sample System Blank
170 with internal glue line	1	80.1 82.3 89.8	77.4 79.6 87.1
	2	87.4 88.0 89.2 90.6	84.7 85.3 86.5 87.9
	3	92.1 93.1 89.7 92.9	89.4 90.4 87.0 90.2
160 with internal glue line	1	93.9 92.0 94.0	91.2 89.3 91.3
	2	84.5 87.2 82.7	81.8 84.5 80.0
	3	88.0 80.0 82.3	85.3 77.3 79.6

Pleat Number	Filter Number	% Efficiency	% Efficiency After Correction For Sample System Blank
150 with internal glue line	1	87.8	85.1
		80.2	77.5
		89.9	87.2
	2	81.4	78.7
		79.2	76.5
		85.2	82.5
	3	87.5	84.8
		86.1	83.4
		88.0	85.3
	4	89.2	86.5
		84.6	81.9
		86.5	83.8
		85.9	83.2
		79.1	76.4

The above data is summarised in Table 4.12

Table 4.12
Summary of Filter Test Data

Filter Pleat Number	Filtration Efficiency Arithmetic Mean (%)	95% Confidence Limits	Standard Deviation
200	83.1	81.3 – 84.9	4.73
190	84.7	83.1 – 86.4	4.34
180	85.6	84.5 – 86.7	2.76
170	86.5	84.6 – 88.3	4.90
160	85.9	84.3 – 87.6	3.67
150	84.1	82.0 – 86.1	4.63
140	83.1	80.6 – 85.6	3.23
130	77.0	71.4 – 82.5	8.30
170 with internal glue line	86.0	83.2 – 88.7	4.14
160 with internal glue line	84.5	80.5 – 88.5	5.22
150 with internal glue line	82.3	80.2 – 84.5	3.63

4.6.2 Backpressure Versus Pleat Numbers

Initial backpressure measurements on filters of different pleat numbers after varying operating hours are provided in Table 4.13.

Table 4.13
Filter Backpressure Vs Operating Hours

Filter Pleat No.	Hours of Operation	Backpressure (kPa)
200	2.0	4.6
	3.3	4.7
	5.3	3.7
	7.8	5.2
	10.4	6.7
	12.2	7.0
170	2.6	4.2
	7.6	5.7
	10.6	7.0
	13.6	6.7
170 with internal glue line	3.0	2.2
	6.0	4.5
	7.5	2.5
	10.0	2.7
	13.0	4.5
	16.0	4.0
150 with internal glue line	3.2	3.0
	6.7	4.0
	11.0	5.0
	14.7	5.5
	18.3	7.7

At the conclusion of the backpressure trials it was decided to retest the used filters to see if the filtration efficiency had altered as a result of being in operation for a number of hours. The results of these tests are listed in Table 4.14.

Table 4.14
% Filtration Efficiency of Used Filters

Pleat No.	Arithmetic Mean Filtration Efficiency (%)	95% Confidence Limits	Standard Deviation	Hours of Use
200	86.6	80.0 – 93.2	2.66	12.2
170	87.9	86.0 – 89.8	2.10	13.6
170 plus glue line	88.1	83.3 – 93.0	1.94	16.0
150 plus glue line	77.5	65.5 – 89.4	7.50	18.2

4.7 DISCUSSION OF RESULTS

4.7.1 Filtration Efficiency Versus Pleat Numbers

The process of evaluating filters for their efficiency against a contaminant of concern is common. However, limited research on this aspect has been conducted on DDEFs. By using the test rig described in section 4.5.3, in excess of 500 elemental carbon analyses were performed on 69 individual filters with 11 individual pleat patterns. A summary of these results (corrected for the test system blank) is provided in Table 4.12.

Statistical examination of the raw data for the filter efficiency tests indicated nine of 11 data sets followed a normal distribution (Table 4.15).

The test used to determine if the data followed a normal distribution was the W-test developed by Shapiro and Wilk (1965). The W-test is based on equations using the slope of the regression line in addition to a generalised least squares technique to correct for observations being ordered and not uncorrelated. To facilitate this process Shapiro and Wilk (1965) have developed tables of percentage points at various confidence levels, against which values calculated from the following equation are compared.

$$W = \frac{\left[\sum_{i=1}^{k} a_i \left(x_{[n-i+1]} - x_{[i]}\right)\right]^2}{s^2(n-1)}$$

Where a_i is a coefficient derived from the sample number and k where k is the number of samples divided by 2 (Shapiro and Wilk 1965).

If the calculated value (W) is greater than the percentage point ($W\alpha$) then the distribution is not rejected.

Thus in Table 4.15 the null hypothesis (H_0) is that if $W_T > W_{0.05}$ then the data follows a normal distribution at the 95% confidence level. The alternate hypothesis (H_A) is that if $W_T < W_{0.05}$ then the data does not follow a normal distribution at the 95% confidence level.

Table 4.15
Normality Tests for Filter Efficiency Data

Pleat No.	No. of Samples	Shapiro-Wilk (W_T)	ρ	$W_{0.05}$	Null Hypothesis
200	29	0.8910	0.0060	0.926	Rejected
190	29	0.9443	0.1301	0.926	Not Rejected
180	28	0.9333	0.0745	0.924	Not Rejected
170	30	0.8597	0.0011	0.927	Rejected
160	22	0.9348	0.1546	0.911	Not Rejected
150	22	0.9565	0.4225	0.911	Not Rejected
140	9	0.9413	0.5957	0.829	Not Rejected
130	11	0.8994	0.1815	0.850	Not Rejected
170G	11	0.8769	0.0951	0.850	Not Rejected
160G	9	0.9214	0.4037	0.829	Not Rejected
150G	14	0.9027	0.1234	0.874	Not Rejected

Two data sets (200 and 170 pleats) indicated a degree of negative skewness. However, plots of each set of data against a cumulative frequency distribution indicated the influence of two results in each data set. On this basis it was considered that each dataset would follow a normal distribution if more samples had been collected. Censoring of these data points and re-analysis proved this assumption to be correct.

In general the variability in results was higher than expected given that the testing process aimed to minimise as many variables as possible.

A comparison of the arithmetic means of filtration efficiency versus pleat numbers gives rise to the following observations:

- The linear regression of pleat numbers versus % filtration for 200 to 130 pleats (Table 4.12) shows little correlation (R^2 = 0.29), however a graphical representation indicates an increase in % filtration as pleat numbers decrease from 200 to about 165, followed by a rapid decrease in % filtration as the pleat numbers decrease from 165 —130 (Figure 4.7). The increase in efficiency with decreasing pleat numbers appears to result from more filter media surface area being available as the individual pleats are not forced together by the exhaust. Below 165 pleats the filtration capacity of the filter media is exceeded and migration across the media occurs.

- The linear regression of pleat numbers versus % filtration for 200 to 160 pleats (Table 4.12) shows a reasonable correlation (R^2 = 0.78) (Figure 4.8) with an excellent correlation (R^2 = 0.98) being achieved at 200 – 170 pleats (Figure 4.9).

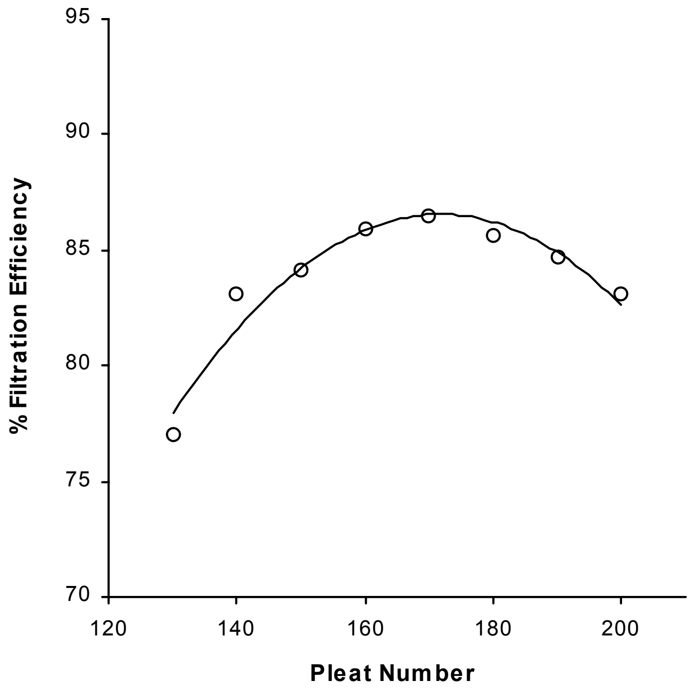


Figure 4.7
Filtration Efficiency Vs Pleat Nos. (200 – 130)

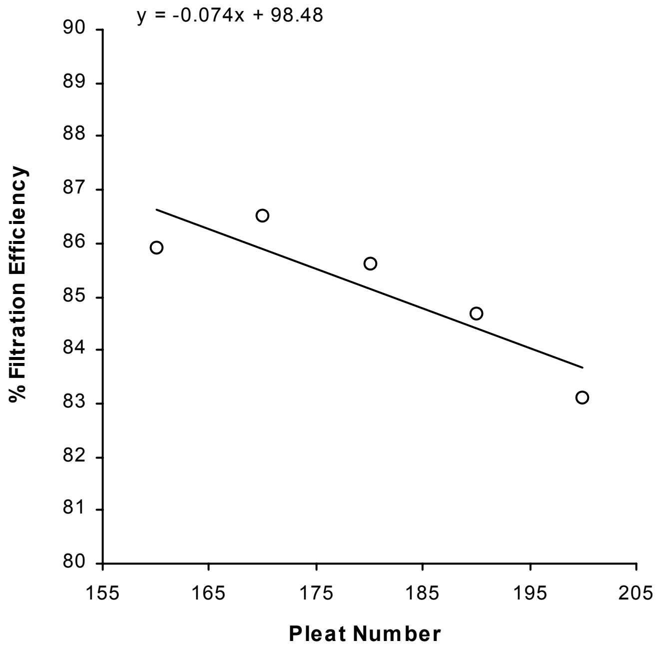


Figure 4.8
Filtration Efficiency Vs Pleat Nos. (200 – 160)

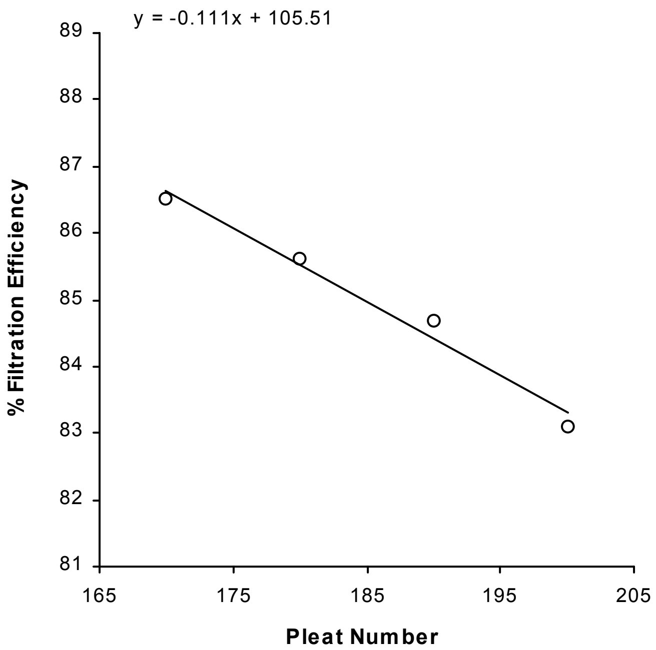


Figure 4.9
Filtration Efficiency Vs Pleat Nos. (200 – 170)

On this basis it can reasonably be concluded that reducing the filter pleat numbers from the current 200 to 170 would increase the filtration efficiency against elemental carbon by approximately 3.4%. A further reduction to 160 pleats would reduce the improvement in filtration efficiency to approximately 2.8%. Further reductions in pleat numbers to 150 and 140 pleats would result in decreases in the filtration efficiency, however the mean % filtration for 200 and 140 pleats is the same. A further reduction in pleat numbers to 130 pleats results in a rapid decrease in filtration efficiency and increased variability.

Examination of the filters treated with an internal glue line to hold the pleats apart, led to the following observations:

- The linear regression of average % filtration (34 samples) versus pleat numbers indicates an excellent correlation (R^2 = 0.99) (Figure 4.10). However, as only 34 samples covering three (150, 160 and 170) pleat sizes could be sampled no significance can be drawn from this correlation.

- Decreasing pleat numbers results in a marginal decrease in % filtration (0.5 – 1.8%) as against no glue line filters of the same pleat number, most probably due to the increased surface area of the media resulting from the pleats being held open by the glue, allowing an increased amount of smaller particles to pass through the filter before mechanical filtration reduces this effect.

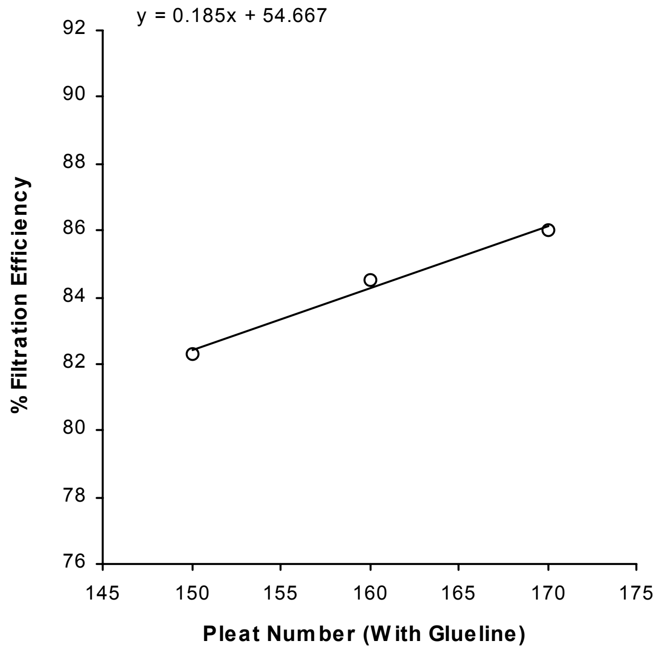


Figure 4.10
Filtration Efficiency Vs Pleat Nos. (with glue line)

4.7.2 Backpressure Versus Pleat Numbers

At the commencement of each backpressure test, new filters were found to have very low backpressures (typically 0.25 kPa) but after a short operating period the backpressure had substantially increased. This was due to the filter acting as a condenser resulting in the filter becoming saturated in water carried over from the scrubber tank.

Linear regressions for the four data sets in Table 4.13 indicated reasonable correlations in three out of four cases (Table 4.16).

Table 4.16
Correlation Coefficients For Filters

Pleat No.	Sample Nos.	R^2
200	6	0.72
170	4	0.87
170 plus glue line	6	0.28
150 plus glue line	5	0.94

Examination of the data set for the filter with 170 pleats and an external glue line suggested the data set was overly influenced by one backpressure reading at six hours of operation. Censoring of this reading within the data set improved the correlation (R^2 = 0.75).

Using the linear regression equations and normalising all filters to 7 kPa (the maximum recommended value for an engine), the filter life for each would be as indicated (Table 4.17).

Table 4.17
Operating Hours at 7 kPa

Pleat No.	Operating Hours @ 7 kPa Maximum BP
200	13.0
170	13.0
170 plus glue line	31.8 (sensored data set)
150 plus glue line	17.7

Clearly the value for 170 pleats with a glue line is significantly different from that for a filter with a similar number of pleats but without the glue line. This, and the lack of robustness in the data set, suggests that this value is an anomaly and the true value for a filter with 170 pleats and a glue line should lie between 13.0 and 17.7 hours of operation at a maximum backpressure of 7.0 kPa.

It is interesting to note that no difference in operating hours is achieved by reducing the pleat numbers from 200 to 170 but an extra 4.7 hours is achieved by reducing the pleat numbers to 150 and incorporating a glue line on the inside of the filter. The excellent correlation (R^2 = 0.94) between operating hours and filter backpressure at 150 pleats (plus a glue line) (Table 4.13) supports this conclusion.

4.7.3 Examination of Used Filters

A comparison of pre and post use filtration efficiencies (Table 4.18) indicates all filters except the 150 pleat filter with an internal glue line, increased in % filtration efficiency. Discussions with the filter manufacturer (Microfresh Filters Pty Ltd) suggest that the increase in % filtration is probably due to mechanical filtration becoming a factor. This results from the particles building up on the filter media and in effect acting as its own filter media.

Table 4.18
Comparison Pre and Post Use Filtration Efficiencies

Pleat No.	Pre Use Efficiency (%)	Post Use Efficiency (%)
200	83.1	86.6
170	86.5	87.9
170 plus glue line	86.0	88.1
150 plus glue line	82.3	77.5

To better understand why the 150 pleat filter had not shown the same increase in % filtration efficiency post use, a number of used filters were cut open, the filter media removed and examined visually.

Figure 4.11 demonstrates that the 200 pleat filter had numerous sections of unused filter media where the pleats had been forced together, thus effectively reducing the surface area of the filter, with a resultant increase in backpressure.

This situation was less in the 170 pleat filter (with an internal glue line), however sections of unused filter media were clearly visible. The 150 pleat filter (with an internal glue line) had almost total surface coverage and close examination of the deposit indicated it to be very thick in some sections, indicating potential filter overload. On this basis it is reasonable to conclude that at 150 pleats the filter load is excessive and thus some material may be migrating through the filter thus resulting in reduced filtration efficiency.

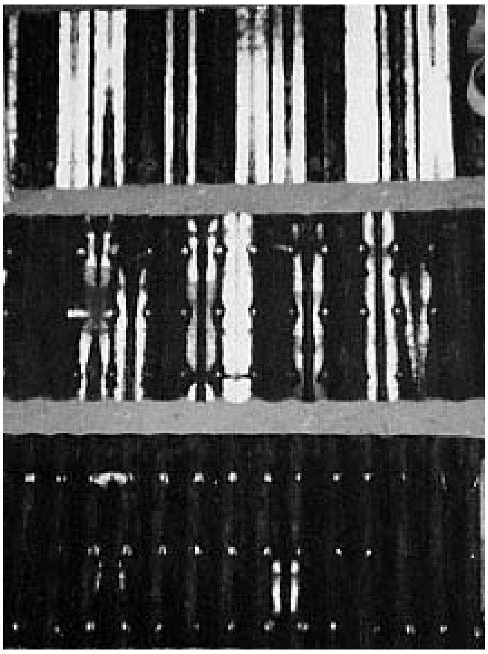


Figure 4.11
Photograph of Used Filters
(Top – 200 pleats, Centre – 170 pleats & glue line, Bottom – 150 pleats & glue line)

Given the above filtration efficiency results and the visual examination of used filters, it is expected that a filter of 160 pleats with an internal glue line should provide a post filtration efficiency of approximately 88% after a short period in use, given that the initial filtration efficiency of the 170 and 170 glue line filters were very similar to that of the 160 pleat filter (86.5% and 86.0% as against 85.9%). The increased surface area of 160 pleats versus 150 pleats should reduce the possibility of overloading under similar operating conditions.

4.7.4 Recommendation For Mine Trial

As a result of the testing previously detailed, discussions were held with BHP Billiton Illawarra Coal and Microfresh Filters Pty Ltd in regard to a large-scale trial of a reduced pleat filter design.

It was agreed that use of a filter with 160 pleats and an internal glue line should provide the following benefits:

- A slight increase in the initial filtration efficiency over the current 200 pleat filter (84.5% from 83.1%) rising to approximately 88% as the filter is used.

- A significant reduction in backpressure resulting in increased filter life.

- Improved filter media coverage.

- Reduced operating costs due to increased filter life and reduced filter media content.

As a result of these discussions a one month trial was held at Elouera Colliery in February and March 2003.

4.8 MINE TRIAL OF 160 PLEAT FILTERS

4.8.1 Trial Protocol

As the first step in developing a protocol to trial 160 pleat filters (with an internal glue line) under operational conditions, a meeting was held with the Occupational Health & Safety Committee of Elouera Colliery. The meeting was provided with a summary of the research project and outcomes to date and asked their opinion as to how a mine trial should proceed.

Resulting from these discussions it was decided that the trial should occur during the forthcoming longwall changeout, as this represented the maximum vehicle usage within the mine at any one period. It was also recommended that for the duration of the trial only mine fitters change filters rather than operators (which was normal practice) as this would provide a better chance that filters would be recovered.

For the trial the following protocol was adopted.

- Fitters would change filters during the period of the trial.
- The hour meter of the vehicle would be read prior to inserting a new filter and the reading recorded on the filter endplate.
- The hour meter of the vehicle would be recorded at the removal of a used filter and recorded on the filter endplate.
- Filters would be changed once per calendar day and only changed prior to this if the vehicle performance was affected.
- The vehicle number and type would be recorded on the endplate of used filters.
- All used filters would be bagged and returned to a central point in the surface workshop for further testing.

To reinforce the importance and benefits of this project, a short presentation was developed which was used at pre-shift meetings to inform the workforce about the project.

4.8.2 Trial Difficulties

During the course of the project a number of issues arose which influenced the scope of the trial. These included:

- Use of 200 pleat filters from hidden stocks.
- Incorrect hour meter times on filters.
- No hour meter times on filters.
- No identification of vehicles on filters.
- Non return of filters to surface workshop.

- Damage to filters in post use transport.

- Damage to filters while in use (identified as resulting from incorrectly adjusted canister lids).

This resulted in only 21 usable filters being available for post use evaluation. These 21 filters covered four types of diesel vehicles and nine individual machines (about 30% of the site vehicles).

4.8.3 Results

All usable filters were tested for backpressure, the results of which are recorded in Table 4.19.

Table 4.19
Backpressure Tests on Used 160 Pleat Filters

Vehicle	Total Operating Hours	Backpressure (kPa)
PJB 136	21	5.2
PJB 137	43	6.7
MPV 105	5	5.0
MPV 105	10	10.0
MPV 105	16	11.2
MPV 127	3	2.5
MPV 203	2	3.0
MPV 203	2	3.0
Ram Car	24	(1) 1.5
Ram Car	24	(2) 1.2
Ram Car	18	(1) 3.2

Vehicle	Total Operating Hours	Backpressure (kPa)
Ram Car	18	(2) 2.7
PJB 136	44	5.2
MPV 129	16	4.7
PJB 137	47	6.0
MPV 129	8	2.7
MPV 129	11	5.2
MPV 129	12	5.5
MPV 127	2	2.7
MPV 104	8	2.2
Eimco 81	3	0.7

A number of filters, representing the longest operating hours, were also tested for filtration efficiency, as indicated in Table 4.20.

Table 4.20
Post Use Filtration Efficiencies of 160 Pleat Filters

Vehicle	Operating Hours	% Filtration Efficiency
MPV 105	16	77.1
PJB 136	44	77.5
Ram Car	24	71.5

It should be noted that the Ram Car was fitted with a twin filter system that included a water reduction device.

For further comparison a filter used for 44 hours was cut open and compared to a 200 pleat filter used on the same vehicle but for 31 hours (Figures 4.12 and 4.13).

Figure 4.12
Filter Media After 44 Hours Use (160 Pleats)
(Top – inlet side of filter; Bottom – outlet side of filter)

Figure 4.13
Filter Media After 31 Hours Use (200 Pleats)
(Top – inlet side of filter; Bottom – outlet side of filter)

A number of interesting observations can be made on the above results. For example, it is clear that not all vehicles operate for extended hours in any 24 hour period (six were below five hours) and thus the arbitrary changing of filters each shift can in many instances be wasteful.

Other observations include:

- In all except two cases the maximum backpressure measured was below 7 kPa, even though some filters had been in use for up to 47 hours.
- Examination of the post filter efficiency tests indicate results to be below that anticipated. Visual examination of some filters (Figures 4.12 and 4.13) indicate some breakthrough, although it appears to be significantly less with the 160 pleat filter than that of a 200 pleat filter used on the same vehicle for 13 hours less.
- The two highest backpressures were measured on filters used on the same vehicle on successive days, suggesting a critical fault with the vehicle engine or canister.

In summary, the mine trial demonstrated that 160 pleat filters could successfully be used for a minimum period of a calendar day (more in some cases) with resultant backpressure being, in the majority of cases, below 7 kPa. Moreover, post use filtration efficiency tests indicate that even after use for periods up to 44 hours the filtration efficiency of the 160 pleat filter would be approximately 75%.

Based on the results of these trials, BHP Billiton Illawarra Coal informed Microfresh Filters Pty Ltd of their intention to only use 160 pleat filters in their operations. Supplies of 160 pleat filters commenced on 1 September 2003.

4.8.4 Estimated Cost Savings

Discussions with Microfresh Filters Pty Ltd and 3M Australia Pty Ltd indicated that no cost savings would arise from the reduction in pleat numbers from 200 to 160 for approximately six months. This was due to the fact that the filter packs were imported from the USA pre-cut to 200 pleats and some effort was needed to re-cut them to 160 pleats.

After current filter pack stock was exhausted a cost saving of $6/filter was anticipated.

Based on filter usage by BHP Billiton Illawarra Coal of 7,500 filters in 2002/2003, this would amount to $45,000.

While accurate figures on filter use during any 24 hour period is hard to isolate into shifts, a review of diesel vehicle movements over several days at one mine indicated that the majority occur on day shift, approximately 50% less occur on afternoon shift and 80% less on night shift. Thus if filters were only changed once per calendar day, only about 60% of the normal filter use would be required.

Based on the 2002/2003 filter usage, this equates to a saving of 3,000 filters per year at a cost saving of $349,200 per annum on current costings.

Unfortunately, such major cost savings will only come with a change in workforce culture to changing filters. Such culture changes are difficult to implement and notoriously difficult to maintain in the coal mining industry.

While these savings are substantial, it is clear that further savings are possible if filter life could be extended by the use of an accurate backpressure indication system and an efficient water removal system.

Such devices are currently being developed and trialled by a number of equipment manufacturers. This approach is more likely to have long term success than one based on culture change.

4.9 CONCLUSIONS

There is little doubt that DDEF currently provide the most effective means of minimising employee exposure to diesel particulate in underground coal mines. While Ambs and Hillman (1992) had demonstrated the effectiveness of the concept, the use of cellulose filters gave rise to considerable concern and led to the sourcing of non-flammable filter media (Pratt et al 1995).

Since the introduction of DDEFs in 1992, little work has been performed on establishing their filtration characteristics to the contaminant of concern.

This project has successfully developed a suitable test procedure that can quickly be used to evaluate potentially new disposable filter designs for suitability in respect to filtration efficiency and backpressure.

Application of this test procedure to the DDEF used within BHP Billiton Illawarra Coal has enabled improvements to be made, which improve the filtration efficiency and lower backpressure.

These improvements, coupled together with a change in work practice in respect to filter changeout times, may result in estimated savings of approximately $395,000 per annum, provided BHP Billiton Illawarra Coal can bring about workforce culture change or establish effective means of identifying to the operator when the filter backpressure has reached an operational limit. If this occurs, cost savings in excess of those indicated would be realised.

5. THE INFLUENCE OF MAINTENANCE PROCEDURES ON RAW EXHAUST DIESEL PARTICULATE CONCENTRATIONS

5.1 INTRODUCTION

The importance of engine tune was first recognized over 100 years ago as demonstrated by the statement *"It is of particular importance that the fuel entering at the mouth should be thoroughly consumed and without the formation of soot",* made by Rudolf Diesel in an application for a US patent on 8 August 1898 (MSHA 2003).

It was also recognized at an early stage (Holz 1960) that engine wear with service invariably resulted in increased exhaust emissions of carbon monoxide. For this reason a statutory raw exhaust gas monitoring programme has been in effect within the NSW underground coal mining industry since the 1950's. More recently the relationship between engine maintenance and other emissions (including diesel particulate) has been investigated for engines typically used in underground mines (Waytulonis 1985).

Since the rise in concern as to the potential adverse health effects of diesel particulate, greater focus on engine maintenance practices has occurred, with one major study (McGinn 2000) in the Canadian mining industry setting the benchmark for others to follow. This study was undertaken within the Canadian underground metalliferous mining industry and no comparative study appears in the literature for the underground coal mining industry.

Given the differences in equipment and operational systems between these two industries it was thought appropriate that an attempt be undertaken to establish if typical maintenance practices within the NSW underground coal industry impact on the level of diesel particulate in the raw exhaust of engines.

To this end, a programme was established to measure the elemental carbon concentration in the raw exhaust of as many vehicles within the BHP Billiton Illawarra Coal diesel fleet and to attempt to establish the reasons for any engines with abnormal results.

5.2 AIM OF PROJECT

The aim of this project was to establish if a routine monitoring programme to determine the elemental carbon concentration in the raw exhaust would be successful in identifying engines with unacceptable emission characteristics.

Moreover, the project aimed to identify the reasons why particular engines have significantly higher exhaust elemental carbon concentrations and determine if this was related to maintenance factors.

5.3 HISTORICAL OVERVIEW

In considering the history of maintenance research in regard to emissions from diesel engines, the discussion has been restricted to that relevant to the underground mining industry.

The first apparent reference to maintenance and emissions within the mining industry is Holz (1960) who recounts research in the United Kingdom during the early 1950's where the performance of diesel locomotives in coal mines was observed for a period of approximately two years. In this case when locomotives were under full load pulling a train upgrade, the concentration of carbon monoxide in the exhaust increased with time or mileage in service. In one case the raw exhaust concentration reached 4,000 ppm after 10,000 miles (16,000 km) of service.

Holz (1960) went on to state that at that time the US Bureau of Mines had not had the opportunity to make a detailed study of maintenance requirements for engines used in mining operations. He did however indicate that some interesting information had been accumulated, the synopsis of which is:

- Fuel injection may have an important effect on combustion. Leaking injection valves caused an increase in raw exhaust carbon monoxide and aldehyde concentrations.

- Only engine manufacturers' designed parts should be used as replacement in engines. This related to an incident where a different injector-nozzle design caused a substantial increase in raw exhaust oxide of nitrogen levels.

- A blockage of injectors or excessive wear would cause a change in fuel distribution and probably an undesirable change in the composition of exhaust gases.

By 1977 the underground mining industry had collected substantial data to better understand the effect of maintenance on emissions. A good insight into progress since 1960 is provided in the proceedings of a workshop on the use of diesel equipment in underground coal mines (NIOSH 1982) held in Morgantown WV from 19-23 September 1977.

At this symposium speakers from Australia, Canada, South Africa and the USA either raised the issue of maintenance on emission generation or referenced statutory maintenance requirements designed to control emissions. An industry "Emissions and Control Technology Work Group" also reported at the symposium and concluded that both engine and exhaust treatment are very important in emission control.

They suggested that maintenance could be divided into two categories – a) preventative maintenance and b) major overhaul, and suggested significant items to be considered under each. These were:

a) **Preventative Maintenance**

- Filters: fuel, air
- Exhaust Treatment: scrubber system, catalytic converter
- Cooling
- After cooling
- Timing
- Injectors
- Flame trap (inlet and exhaust)

b) **Major Overhaul**

- Utilisation of original manufacturers' parts
- Replacement of all critical components
- Engine emission performance under load after overhaul

The most detailed early research on the effects of maintenance and service duration on diesel engine exhaust emissions appears to be that of Waytulonis (1985). In this study six Caterpillar 3306 PCNA and seven Deutz F6L 912W engines with varying amounts of service life were sourced from five mines. Also a new Deutz F6L 912W engine was used to determine the effects of maladjustments or faults on the production of hydrocarbons, carbon monoxide, oxides of nitrogen and particulate matter.

Waytulonis (1985) concluded that in the absence of severe faults or maladjustments, exhaust emission quality did not excessively change during the initial 4,000 hours of service life. After about 4,000 – 5,000 hours the engines examined exhibited the following trends: hydrocarbons increased, carbon monoxide increased, oxides of nitrogen decreased and particulates increased.

Waytulonis (1985) also induced a number of faults in a new Deutz F6L 912W engine and examined their effect on exhaust emissions. Specific observations from this research were:

- The production of hydrocarbons is most affected by fuel injection timing maladjustments (increase of 306% over baseline values when retarded 4° and increased 106% when advanced 4°). The restriction of intake air in combination with injection timing maladjustment resulted in hydrocarbon increases of up to 443%.

- Increased carbon monoxide levels in the engine exhaust occurred when an intake air restriction was present with over-fuelling (increase of 164 – 445%).

  Over-fuelling, combined with an exhaust restriction, resulted in an increase of 102 – 326%, while over-fuelling on its own resulted in carbon monoxide increases of 95 – 247%.

- The single fault most severely affecting oxides of nitrogen production was fuel injection timing (increase of 50% at 8° advance and a reduction of 33% with 4° retard).

- The single faults which increased particulate levels were intake air restriction (44 – 164%) and over-fuelling (125 – 173%). When both these faults occurred at once, particulate generation increased by 1038% over previously recorded baseline values.

Waytulonis (1985) concluded that all the above conditions could be traced to five specific maintenance activities:

1. Intake air filter changeout frequency
2. Fuel injection timing adjustment
3. Fuel rate adjustment
4. Fuel injector nozzle cleaning and/or changeout
5. Exhaust restriction monitoring

The most extensive study of the relationship between diesel engine maintenance and exhaust emissions is that reported by McGinn (2000). This project, conducted under the Diesel Emissions Evaluation Programme (DEEP) in Canada, was centred on Falconbridge Ltd Strathcona Mine in Onaping, Ontario. The project involved a small group of people (five in total) with extensive experience in maintaining diesel engines on underground equipment, developing a maintenance guideline based on their accumulated experience. The resultant guideline focused on two areas; engine systems and operational issues. The engine systems' issues were then prioritized under the following items:

- Intake system
- Exhaust system
- Fuel injection
- Engine cooling
- Fuel quality and handling
- Lubrication

The operational issues considered critical to proper engine maintenance were:

- Attitudes
- Training
- Tools
- Process and practices
- Programmed maintenance and engine repairs

This guideline was then used to build an action plan for implementing improved maintenance.

At the heart of this process was the need for a means of measuring the emission quality of engines as the project progressed.

This was achieved by the use of an undiluted gas analysis system (UGAS) capable of measuring oxygen, carbon monoxide, nitric oxide, nitrogen dioxide, sulphur dioxide, hydrocarbons and temperature. Diesel particulate matter was also collected using a high flow pump drawing 12 litres of exhaust through a pre-weighed filter. The filter was post-weighed and the concentration calculated. After a period of time, maintenance personnel became skilled at visually interpreting the discolouration of filters.

Using the above equipment, baseline data was collected from 13 scoop trams powered by four different engine types and covering mid to high range horsepower ratings. An audit of current practices at Strathcona Mine was undertaken and the following points identified.

- Fuel handling underground was seen to be below standard with fuel storage cubes contaminated with dirt, garbage and water. An upgraded system for the management of fuel was implemented.

- Recycled oil intended for top-up purposes only was being used as a primary source rather than new oil. Recycled oil use was discontinued.

- The existing scheduled maintenance programmed was felt to lack proper focus on specific systems in respect to engines. A set of engine system diagnostic preventative maintenance items was developed and scheduled for completion at 250 hour intervals.

Following the rectification of the audit deficiencies and the introduction of a diagnostic preventative maintenance programmed for engine systems, the exhaust of each unit involved in the case study was re-tested.

The outcome was very positive in that carbon monoxide levels were reduced by up to 65% and by up to 55% for diesel particulate matter.

The key learning outcomes stressed by McGinn (2000) were:

- There is a need to have a team approach to maintenance and that the team should involve mechanics, operators, supervision, planning and management. For the team to be effective it needed to have sufficient time, tools, training and resources.

- There is a need to conduct an audit of engine maintenance at least once per year.

- There is a need to create and implement a strategy for improving existing maintenance practices to reduce diesel emissions.

- Testing of undiluted exhaust emissions is fundamental to any successful programme. There is a need to set action limits on emissions to ensure response to problems.

- Use the services of suppliers to train and update maintenance personnel.

There is little doubt that the work of McGinn (2000) sets the benchmark for effective maintenance programmes within the underground metalliferous mining industry, however similar research does not appear to have occurred on the same scale within the underground coal industry.

Davies (2000), when examining the range of raw exhaust elemental carbon concentrations recorded on eight engines of the same type used in a NSW coal mine, suggested maintenance as a possible factor for the difference.

To test this theory one engine was removed from service and basic maintenance procedures performed and the engine re-tested. In this case the act of cleaning out the flame trap in an ultrasonic bath and replacing the air intake filter resulted in a reduction of up to 71% in raw exhaust elemental carbon levels. Discussions with mine personnel indicated that the flame trap was only cleaned if visually dirty and the case in question the flame trap was not considered to be visually dirty. This emphasizes the need for good diagnostic tools to help maintenance personnel maintain engines to optimum emission performance.

Routine raw exhaust gas monitoring data collected by the NSW Department of Mineral Resources (1999) suggests in some mining districts that over-fuelling of engines may be occurring within the NSW coal industry. No evidence exists to suggest that this has been adequately explored.

Recently the process of derating engines has been suggested as a means of reducing diesel particulate emissions (Schnakenberg and Bugarski 2002). Reductions of up to 55% in particulate emissions have been quoted but with a resultant loss in power (7%). The practice of derating appears to have favour in the high altitude mining communities of the USA but is not normally practised within Australia. The use of low emission fuels has already resulted in some power loss so the impost of another power loss factor would not be viewed favourably within the Australian mining industry.

Given the above, it is clear that maintenance can impact on emission levels from the exhaust of diesel engines and any process to identify key maintenance issues would be of benefit, especially in the underground coal mining industry. This project aimed to examine the diesel fleet at four underground coal mines and establish any maintenance factors affecting emission quality.

5.4 METHODOLOGY

5.4.1 Introduction

The routine analysis of the raw exhaust of diesel engines used in the NSW coal industry for toxic gases has been undertaken for approximately 50 years. In the early 1970's mobile gas laboratories (Figure 5.1) were introduced and the raw exhaust tested according to statutory requirements (NSW Department of Mineral Resources 1995).

Figure 5.1
Mobile Gas Laboratory

This process has been very successful in controlling gaseous emissions within underground coal mines and is an excellent model for sampling for diesel particulate. Spears (1997) also recognized the success of the NSW system and commented:

> *"The Australian method of on-site emission testing provided the best model for the development of the EAMP (Emissions-Assisted Maintenance Procedure for Diesel-Powered Equipment)."*

Given the above, and the availability of the Rupprecht & Patashnick Co Inc Series 5100 Diesel Particulate Measurement System, the linkage of the mobile gas laboratory and the Series 5100 Analyser presented a powerful diagnostic tool with which to examine in-service engines.

Using these tools, the raw exhaust of 66 individual diesel engines currently operating within the BHP Billiton Illawarra Coal diesel fleet, were tested over a seven month period and any abnormal results investigated.

5.4.2 Sampling Equipment and Procedures

Sampling and analysis for gaseous emissions was performed using the services of the Coal Mines Technical Services Pty Ltd (CMTS) mobile gas analysis laboratory. This unit is NATA certified and approved by the NSW Department of Mineral Resources under the requirements of MDG 29 (NSW Department of Mineral Resources 1995).

The laboratory has the facility to analyse raw diesel exhaust for carbon dioxide, carbon monoxide using Horiba PIR 2000 infrared analysers and for oxides of nitrogen using a Thermo Electronics Corporation Chemiluminescence Analyser. Instrumentation was calibrated using certified gas mixtures according to NATA requirements.

Sampling for organic, total and elemental carbon was performed using the R&P Series 5100 diesel particulate analyser (Figure 5.2), previously described in section 3 of this thesis. Duplicate samples were collected and the average value recorded.

Figure 5.2
R&P Series 5100 Analyser and Mobile Gas Laboratory on-site during testing of an EIMCO LHD

The testing of engines was performed in accordance with section 4.1 of MDG 29 (NSW Department of Mineral Resources 1995) under torque stall conditions. Each engine was operated at full throttle with sufficient load being added to bring the engine speed down from its maximum by 200 – 300 rpm. A satisfactory load is achieved under these conditions when the raw exhaust CO_2 content is not less than 6% by volume.

A number of issues arose during the exercise which impinged on the number of engines tested or analysis procedures. These were:

- Several units had exhaust systems that did not allow a flexible pipe to be connected without leaks. These were typically slot exhausts, some of which were located in inaccessible areas of the vehicle. Such exhausts would need to be redirected if these vehicles were to be included in future sampling programmes.

- A number of units were out of service for scheduled maintenance or off site for extended repairs. These units could not be sampled.

- On a number of occasions the CMTS mobile laboratory was unavailable on the day when vehicles were available for particulate testing. In such cases either the last statutory gas test on the vehicle was used (providing it had been collected within a reasonable timeframe of the particulate sample) or a gas test was conducted on the first available opportunity. In reality such situations rarely occurred.

- As the elemental carbon analyser could not be taken underground, for intrinsic safety reasons, all vehicles had to be sampled on the surface. This presented no difficulties at two mines but at the other two, vehicles had to be specially brought to the surface for testing or testing was integrated into the schedule for vehicles brought to the surface for specific maintenance.

  Due to operational requirements this resulted in the testing programme being drawn out over an extended period.

5.5 STANDARDS

Within NSW there are no current limits for the level of diesel particulate generated from a diesel engine during normal service at an underground coal mine.

Australian Standard AS3584.2 – 2003 recommends that during type testing, soot concentrations should not exceed 50 – 100 mg/m^3 (dependent on nominal gas flow) as measured by the Bosch Smoke Meter. A conversion graph from Bosch units to soot concentration mg/m^3 @ 15.6°C and 760 mm Hg as derived for SAE J 255 is provided. These values are based on testing using the ISO 8178 (1996) weighted protocol. This approach has no practical relevance to engines tested under torque stall conditions in situ.

The US Mine Safety and Health Administration has introduced a statutory requirement (Federal Register 2001) that all engines meet specific emission rates (eg heavy duty equipment 2.5 g/hr DP or light duty engines 5.0 g/hr DP). No information has been provided by MSHA linking this value to workplace exposures or the control of adverse health effects.

Given the lack of clarity at this point in time in regard to raw exhaust particulate limits, it was considered appropriate to adopt a comparative approach to identify abnormal engines within the BHP Billiton Illawarra Coal diesel fleet.

Consequently the elemental carbon results of each engine were compared with the average for that engine type. Those engines exceeding the 95% upper confidence limit of the mean value were deemed to be abnormal. Discussions were held with mine engineers and this approach was considered appropriate given the lack of any statutory guidance.

In relation to gaseous emissions the NSW statutory requirements (NSW Department of Mineral Resources 1995) were adopted. These are:

Carbon Monoxide	1,500 ppm	(load)
Oxides of Nitrogen	750 ppm	(load)

for engines tested under field conditions.

5.6 RESULTS

5.6.1 Number of Engines Tested

During the period 19 June 2003 – 2 December 2003 a total of 66 Individual engines were sampled at four BHP Billiton Illawarra Coal underground coal mines.

Details as to the number of engines of each type tested are provided in Table 5.1.

Table 5.1
Number and Type of Engine Tested

Engine Type	No. of Units Tested
Caterpillar 3304	26
Caterpillar 3306	5
KIA 6-247	12
Perkins 1006.6	14
MWM D916.4	6
MWM D916.6	3

This represents 68% of the BHP Billiton Illawarra Coal diesel fleet; the other units either out of service for repair or having exhaust outlets which did not allow a particulate sample to be collected. Given that this exercise was the first attempt to test the exhaust of in-service units for diesel particulate, the success rate of 68% was considered satisfactory. Lessons learnt during the current exercise will make future exercises easier and should lead to an increased sample collection rate.

Comparison of percentage of engines sampled to that reported by NSW Department of Mineral Resources (2001) for all engines operating in NSW is consistent, with Caterpillar being the most common engine type (Table 5.2).

Table 5.2
Comparison of Engine Type Sampled to Industry Fleet Composition

Engine Make	NSW Mineral Resources (2001)	BHP Billiton Illawarra Coal
Caterpillar	51.5%	47.0%
KIA	16.2%	18.2%
Perkins	12.8%	21.2%
MWM	12.3%	13.4%

5.6.2 Raw Exhaust Elemental Carbon Results

Raw exhaust analysis for organic, total and elemental carbon is provided in Table 5.3.

To enable comparisons between engine types the elemental carbon concentration was calculated in g/kWhr (using the approved rated power for each engine type) and also g/hr.

Table 5.3
Raw Exhaust Elemental Carbon Analysis

Mine	Vehicle	Engine Type	Date Tested	OC mg/m³	TC mg/m³	EC mg/m³	EC g/kWhr	EC g/hr
Elouera	Eimco 122	Cat 3304	19.6.2003	7.1	39	32	0.16	10.1
Elouera	Eimco 81	Cat 3304	19.6.2003	12	42	30	0.17	10.7
Elouera	PJB 136	KIA 6-247	19.6.2003	8	21	13	0.04	2
Elouera	MPV 104	Cat 3304	20.6.2003	8.7	43	34	0.12	7.6
Elouera	MPV 129	Cat 3304	23.6.2003	8.3	71	63	0.2	12.6
Elouera	PJB 327	KIA 6-247 (Supercharged)	23.6.2003	5.6	13	7	0.02	1.5
Elouera	Eimco 124	Cat 3304	23.6.2003	7.5	33	26	0.14	8.8
Elouera	MPV 125	Cat 3304	24.6.2003	9.3	39	30	0.15	9.5
Elouera	PJB 137	KIA 6-247	24.6.2003	19	69	50	0.19	9.5
Elouera	Grader 116	MWM D916.4	25.6.2003	20	69	49	0.37	17.4
Elouera	MPV 203	Cat 3304	26.6.2003	11	58	47	0.19	12
Elouera	Eimco 123	Cat 3304	27.6.2003	7.9	49	41	0.22	13.9
Elouera	MPV 105	Cat 3304	27.6.2003	15	69	54	0.19	12
Elouera	PJB 132	KIA 6-247	1.7.2003	13	152	139	0.53	26.5
Elouera	Eimco 100	Cat 3306	8.7.2003	3.9	9.8	5.9	0.02	1.3
Elouera	Ram Car 194	MWM D916.6	9.7.2003	10	169	159	0.4	30
Elouera	PJB 134	KIA 6-247	29.9.2003	8.8	76	67	0.3	15
Elouera	PJB 114	KIA 6-247	29.9.2003	6.8	35	28	0.1	5
Dendrobium	PJB 116	KIA 6-247	5.8.2003	8.5	51	43	0.23	11.5
Dendrobium	PJB 103	KIA 6-247	5.8.2003	8.2	110	102	0.52	26
Dendrobium	PJB 115	KIA 6-247	6.8.2003	7.2	58	51	0.25	12.5
Dendrobium	Eimco 105	Cat 3304	6.8.2003	6.3	22	16	0.1	6.3
Dendrobium	Grader 30	Cat 3304	6.8.2003	11	36	23	0.1	6.3
Dendrobium	SMV 5155	Perkins 1006.6	7.8.2003	7.2	34	27	0.12	8.4
Dendrobium	Eimco 6	Cat 3304	8.8.2003	7.8	37	29	0.14	8.8
Dendrobium	Wagner 113	Cat 3306	8.8.2003	13	35	22	0.07	7.5
West Cliff	SMV 114	Perkins 1006.6	12.8.2003	6.5	27	21	0.09	6.3
West Cliff	Domino 13	MWM D916.4	12.8.2003	9.9	54	44	0.25	11.8
West Cliff	Eimco 50	Cat 3304	12.8.2003	6.9	30	23	0.1	6.3

Mine	Vehicle	Engine Type	Date Tested	OC mg/m3	TC mg/m3	EC mg/m3	EC g/kWhr	EC g/hr
West Cliff	SMV 117	Perkins 1006.6	14.8.2003	7.8	41	33	0.12	8.4
West Cliff	Domino 6	MWM D916.4	14.8.2003	7.7	44	36	0.14	6.6
West Cliff	PJB 108	KIA 6-247	15.8.2003	12	29	17	0.08	4
West Cliff	PET 98	MWM D916.6	15.8.2003	4.6	27	22	0.05	3.8
West Cliff	Eimco 243	Cat 3306	19.8.2003	9.5	18	9	0.03	3.2
West Cliff	Eimco 205	Cat 3304	26.8.2003	5.4	19	14	0.08	5
West Cliff	PJB 109	KIA 6-247	26.8.2003	6.1	23	17	0.08	4
West Cliff	PET 90	MWM D916.6	1.9.2003	4.7	33	28	0.05	3.8
West Cliff	Grader 100	MWM D916.4	15.9.2003	9.4	71	62	0.32	15
West Cliff	SMV 5019	Perkins 1006.6	15.9.2003	7	27	20	0.07	4.9
West Cliff	SMV 115	Perkins 1006.6	16.9.2003	5.1	22	17	0.06	4.2
West Cliff	Eimco 55	Cat 3304	17.9.2003	6.7	47	40	0.19	12
West Cliff	Eimco 244	Cat 3306	10.10.2003	5.1	9.8	4.7	0.01	1.1
West Cliff	SMV 116	Perkins 1006.6	13.10.2003	6.9	30	23	0.07	4.9
Appin	MPV 96	Cat 3304	16.10.2003	11	19	8	0.02	1.3
Appin	Domino 59	MWM D916.4	16.10.2003	6.4	27	21	0.09	4.2
Appin	Eimco 10	Cat 3304	17.10.2003	19	47	28	0.15	9.5
Appin	Eimco 8	Cat 3304	17.10.2003	11	30	19	0.11	6.9
Appin	SMV 5073	Perkins 1006.6	22.10.2003	12	105	93	0.25	17.5
Appin	SMV 5049	Perkins 1006.6	22.10.2003	5	20	15	0.03	2.1
Appin	SMV 5100	Perkins 1006.6	23.10.2003	8.9	69	60	0.17	11.9
Appin	SMV 5090	Perkins 1006.6	23.10.2003	3.9	16	12	0.03	2.1
Appin	Eimco 7	Cat 3304	24.10.2003	8.4	29	21	0.12	7.6
Appin	SMV 5089	Perkins 1006.6	29.10.2003	6	25	19	0.04	2.8
Appin	SMV 5092	Perkins 1006.6	31.10.2003	7.5	39	32	0.08	5.6
Appin	Eimco 17	Cat 3304	3.11.2003	8	23	15	0.08	5
Appin	Eimco 18	Cat 3304	5.11.2003	7.3	23	16	0.05	3.2
Appin	SMV 5051	Perkins 1006.6	6.11.2003	6.7	24	17	0.05	3.5
Appin	Eimco 25	Cat 3306	12.11.2003	4.6	13	8	0.3	2.7
Appin	SMV 5076	Perkins 1006.6	12.11.2003	7.6	34	26	0.06	4.4
Appin	Eimco 104	Cat 3304	21.11.2003	8.2	41	33	0.11	6.9
Appin	MPV 98	Cat 3304	21.11.2003	19	90	71	0.25	15.9
Appin	PJB 107	KIA 6-247	21.11.2003	11	51	40	0.19	9.6
Appin	Eimco 19	Cat 3304	26.11.2003	8.2	45	37	0.2	12.8
Appin	Eimco 9	Cat 3304	27.11.2003	6.3	33	27	0.11	6.9
Appin	Domino 31	MWM 916.4	28.11.2003	7.6	33	25	0.12	5.5
Appin	Grader 18	Cat 3304	2.12.2003	6.8	21	14	0.05	3.4

The results in Table 5.3 only include those values on the initial test of an engine. On those engines found to be abnormal, further testing post maintenance was performed, the results of which are recorded in Table 5.4.

Table 5.4
Raw Exhaust Elemental Carbon Analysis – Post Maintenance

Vehicle	Date Tested	OC mg/m³	TC mg/m³	EC mg/m³	EC g/kWhr	EC g/hr	Maintenance Performed
PJB 132	30.9.2003	8.6	55	46	0.19	9.5	New fuel pump and cleaned scrubber tank
PJB 114	30.9.2003	14	145	131	0.57	28.5	New scrubber tank
PJB 114	30.9.2003	8.5	53	45	0.19	9.5	Reduced fuel
PJB 114	9.10.2003	5.9	52	46	0.18	9	New injectors
PJB 114	9.10.2003	7.4	47	40	0.17	8.5	Increased fuel
Ram Car 194	6.1.2004	10	81	71	0.15	11.3	Replaced injectors
PJB 103	13.1.2004	11	72	61	0.29	14.5	Replaced injectors, cleaned scrubber tank and intake air system

5.6.3 Raw Exhaust Gas Analysis

Raw exhaust analysis for carbon dioxide, carbon monoxide and oxides of nitrogen are provided in Table 5.5.

Table 5.5
Raw Exhaust Gas Analysis

Mine	Vehicle	Engine Type	Date Tested	CO_2 %	CO ppm	NOx ppm
Elouera	Eimco 122	Cat 3304	19.6.2003	10	180	430
Elouera	Eimco 81	Cat 3304	19.6.2003	10	240	330
Elouera	PJB 136	KIA 6-247	19.6.2003	11	520	240
Elouera	MPV 104	Cat 3304	20.6.2003	10.5	250	370
Elouera	MPV 129	Cat 3304	23.6.2003	11	560	320
Elouera	PJB 327	KIA 6-247 (Supercharged)	23.6.2003	10.5	240	400
Elouera	Eimco 124	Cat 3304	23.6.2003	10.5	280	340
Elouera	MPV 125	Cat 3304	24.6.2003	10.5	220	330
Elouera	PJB 137	KIA 6-247	24.6.2003	12	1025	360
Elouera	Grader 116	MWM D916.4	25.6.2003	11	920	260
Elouera	MPV 203	Cat 3304	26.6.2003	10.5	360	290
Elouera	Eimco 123	Cat 3304	27.6.2003	11.5	350	400
Elouera	MPV 105	Cat 3304	27.6.2003	11	340	330
Elouera	PJB 132	KIA 6-247	1.7.2003	10.5	1250	250
Elouera	Eimco 100	Cat 3306	8.7.2003	10.5	230	360
Elouera	Ram Car 194	MWM D916.6	9.7.2003	10.5	760	250
Elouera	PJB 134	KIA 6-247	29.9.2003	11	700	360
Elouera	PJB 114	KIA 6-247	29.9.2003	11	2000	500
Dendrobium	PJB 116	KIA 6-247	5.8.2003	11.5	550	270
Dendrobium	PJB 103	KIA 6-247	5.8.2003	11.5	1025	350
Dendrobium	PJB 115	KIA 6-247	6.8.2003	11	620	330
Dendrobium	Eimco 105	Cat 3304	6.8.2003	9.5	200	480
Dendrobium	Grader 30	Cat 3304	6.8.2003	10	250	450
Dendrobium	SMV 5155	Perkins 1006.6	7.8.2003	9	250	740
Dendrobium	Eimco 6	Cat 3304	8.8.2003	11	420	320
Dendrobium	Wagner 113	Cat 3306	8.8.2003	10	340	360

Mine	Vehicle	Engine Type	Date Tested	CO_2 %	CO ppm	NOx ppm
West Cliff	SMV 114	Perkins 1006.6	12.8.2003	9.5	380	720
West Cliff	Domino 13	MWM D916.4	12.8.2003	10.5	810	240
West Cliff	Eimco 50	Cat 3304	12.8.2003	11	660	240
West Cliff	SMV 117	Perkins 1006.6	14.8.2003	9	520	560
West Cliff	Domino 6	MWM D916.4	14.8.2003	10.5	610	280
West Cliff	PJB 108	KIA 6-247	15.8.2003	9	320	200
West Cliff	PET 98	MWM D916.6	15.8.2003	8.5	170	320
West Cliff	Eimco 243	Cat 3306	19.8.2003	9.5	220	400
West Cliff	Eimco 205	Cat 3304	26.8.2003	9	380	370
West Cliff	PJB 109	KIA 6-247	26.8.2003	9	250	150
West Cliff	PET 90	MWM D916.6	1.9.2003	8.5	180	100
West Cliff	Grader 100	MWM D916.4	15.9.2003	9	230	200
West Cliff	SMV 5019	Perkins 1006.6	15.9.2003	8.5	300	690
West Cliff	SMV 115	Perkins 1006.6	16.9.2003	8.5	200	720
West Cliff	Eimco 55	Cat 3304	17.9.2003	10	470	420
West Cliff	Eimco 244	Cat 3306	10.10.2003	9.5	170	420
West Cliff	SMV 116	Perkins 1006.6	13.10.2003	8.5	240	660
Appin	MPV 96	Cat 3304	16.10.2003	9	180	400
Appin	Domino 59	MWM D916.4	16.10.2003	8.5	150	260
Appin	Eimco 10	Cat 3304	17.10.2003	9	170	460
Appin	Eimco 8	Cat 3304	17.10.2003	9	210	450
Appin	SMV 5073	Perkins 1006.6	22.10.2003	9	620	720
Appin	SMV 5049	Perkins 1006.6	22.10.2003	8	250	620
Appin	SMV 5100	Perkins 1006.6	23.10.2003	10.5	950	740
Appin	SMV 5090	Perkins 1006.6	23.10.2003	8.5	250	660
Appin	Eimco 7	Cat 3304	24.10.2003	9.5	240	400
Appin	SMV 5089	Perkins 1006.6	29.10.2003	9	320	680
Appin	SMV 5092	Perkins 1006.6	31.10.2003	10	490	740
Appin	Eimco 17	Cat 3304	3.11.2003	9	190	460
Appin	Eimco 18	Cat 3304	5.11.2003	8.5	150	480
Appin	SMV 5051	Perkins 1006.6	6.11.2003	8.5	240	660
Appin	Eimco 25	Cat 3306	12.11.2003	9	150	400
Appin	SMV 5076	Perkins 1006.6	12.11.2003	9.5	550	700
Appin	Emico 104	Cat 3304	21.11.2003	10.5	310	330
Appin	MPV 98	Cat 3304	21.11.2003	10.5	420	350
Appin	PJB 107	KIA 6-247	21.11.2003	11.5	460	290
Appin	Eimco 19	Cat 3304	26.11.2003	11	350	370
Appin	Eimco 9	Cat 3304	27.11.2003	11	510	300
Appin	Domino 31	MWM D916.4	28.11.2003	8.5	190	280
Appin	Grader 18	Cat 3304	2.12.2003	8	150	450

On those engines found to require maintenance, a further raw exhaust gas test was performed, either during or at the completion of the maintenance procedure. These results are listed in Table 5.6.

Table 5.6
Raw Exhaust Gas Analysis – Post Maintenance

Vehicle	Date Tested	CO_2 %	CO ppm	NOx ppm	Maintenance Performed
PJB 132	30.9.2003	11	690	400	New fuel pump and cleaned scrubber tank
PJB 114	30.9.2003	11	>2500	280	New scrubber tank
PJB 114	30.9.2003	10	690	350	Reduced fuel
PJB 114	9.10.2003	9	310	350	New injectors
PJB 114	9.10.2003	11	600	350	Increased fuel
Ram Car 194	6.1.2004	10	620	230	Replaced injectors
PJB 103	13.1.2004	10.5	720	320	Replaced injectors, cleaned scrubber tank and air intake system

5.6.4 Calculation of Acceptance Criteria

As indicated in section 5.5, it was agreed with mine site personnel that the 95% UCL of the mean value for each engine type would be used as the acceptance criteria for raw exhaust elemental carbon. These values are listed in Table 5.7.

The use of the 95% UCL of the mean value for each engine type was considered appropriate as it quantifies uncertainty in the estimate of the arithmetic mean. Thus any engine result above the 95% UCL should be considered an outlier and investigated accordingly.

The 95% UCL for the mean value of each engine type was calculated from the formula

$$95\%\ UCL = AM + t \cdot S/\sqrt{n}$$

Where AM = Arithmetic mean

t = t – Distribution derived from the degrees of freedom and the required level of confidence

S = Standard deviation for the sample size n

n = Sample size

Grantham (2001) indicates that as the number of data points decreases, and thus uncertainty increases, the t-Distribution value (or probability value) is required to account for this increasing uncertainty by increasing accordingly.

Table 5.7
Acceptance Criteria – Elemental Carbon

Engine Type	No. Engines Tested	Mean EC mg/m^3	95% UCL mg/m^3
Caterpillar 3304	26	30	37
Caterpillar 3306	5	10	19
KIA 6-247	12	56	85
Perkins 1006.6	14	30	42
MWM D916.4	6	40	56
MWM D916.6	3	70	262

In respect to the MWM D916.6 engines only three tests were conducted, the results of which were highly variable (SD = 77.4). Application of a 95% UCL under these circumstances was not considered appropriate until the results of further engines became available.

Notwithstanding the above, it became apparent that one engine (Ram Car 194) was high (EC = 159 mg/m^3) in comparison to the other two engines tested (EC = 22 and 28 mg/m^3 respectively) and thus an arbitrary decision was made to declare this engine abnormal.

5.6.5 Abnormal Engines in Fleet

Following the initial testing and after the application of engine acceptance criteria, the following units were deemed to be unacceptable (Table 5.8) and the reasons for elevated emissions investigated.

Table 5.8
List of Unacceptable Engines

Mine	Vehicle	Engine	EC mg/m^3
Appin	SMV 5073	Perkins 1006.6	93
Appin	SMV 5100	Perkins 1006.6	60
Appin	MPV 98	Cat 3304	71
Dendrobium	PJB 103	KIA 6-247	102
Elouera	PJB 114	KIA 6-247	131
Elouera	PJB 132	KIA 6-247	139
Elouera	Ram Car 194	MWM D916.6	159

5.7 DISCUSSION OF RESULTS

5.7.1 Introduction

Over a period of approximately seven months the exhausts of 66 engines from vehicles in service at four underground coal mines were tested for elemental carbon (Table 5.3) in order to identify any abnormal or “dirty” engines. Raw exhaust gaseous emissions were also measured, the results of which are listed in Table 5.5. On the basis of comparison of individual engine raw elemental carbon results to the moving average (95% UCL) of all similar engine results, a total of seven engines were deemed to be unacceptable (Table 5.8).

It should be noted that ram car 194 was included due to its wide divergence from the other two engines tested (variance too great (SD = 77.4) for meaningful 95% UCL with results from only three engines).

As abnormal engines were identified, mine site mechanical engineering personnel were advised and corrective actions instigated. The results of these investigations are discussed in section 5.7.2.

Notwithstanding the identification of abnormal engines and resultant corrective actions, the results in general raise a number of interesting aspects and offer the opportunity to speculate on possible conclusions. The areas of interest include:

- Comparison of data to MSHA certification data
- Comparison to previous Australian monitoring data
- Comparison of West Cliff data to the other mines
- The influence of Eromanga fuel
- Relationship between raw exhaust elemental carbon generation rates and current statutory ventilation guidelines
- Relationship between raw exhaust gas and elemental carbon concentrations

As the project has progressed, the resultant data has sparked mine site interest and the process of routine raw exhaust elemental carbon monitoring has received strong support as a valuable diagnostic tool.

5.7.2 Investigation of Abnormal Engines

Initial investigation of abnormal engines focused on PJB 114 and 132 at Elouera Colliery, albeit for different reasons. The raw exhaust carbon monoxide reading on vehicle 114 was found to be 2,000 ppm CO, well above the statutory limit of 1,500 ppm. At the same time the raw exhaust elemental carbon concentration was only 28 mg/m^3, which was somewhat of a surprise.

During the connection of the sampling hose to the gas point on the engine manifold, it was noticed that the engine appeared to have a very high backpressure. A pressure gauge was used to measure the backpressure between the engine and the water-filled spark arrestor (scrubber tank).

The backpressure recorded was 170 kPa, many times the engine manufacturer's recommendation. Pressure tests across the inlet and outlet of the scrubber tank indicated a restriction and as a result the unit was removed and replaced with a reconditioned unit from the store. Immediately the raw exhaust elemental carbon result increased from 28 to 121 mg/m^3 and the carbon monoxide from 2,000 to >2,500 ppm. The high carbon monoxide concentration suggested over-fueling and the fuel setting was adjusted to a lower rate. Immediately the elemental carbon concentration dropped from 131 to 45 mg/m^3 and the carbon monoxide concentration reduced from >2,500 ppm to 690 ppm.

Following an evaluation by Elouera Colliery mine site engineering personnel it was decided to replace the fuel injectors to establish if better power performance could be achieved. As a result, elemental carbon concentrations barely moved (Table 5.4); however carbon monoxide levels were reduced by over 50% (Table 5.6). This provided the opportunity to readjust the fuel setting to give more power, resulting in a final raw exhaust carbon monoxide concentration of 600 ppm and 40 mg/m^3 elemental carbon.

The initial scrubber tank was returned to the vehicle manufacturer, where the base of the unit was cut open for inspection. As can be observed in Figure 5.3, the majority of exhaust downpipes were blocked with a carbonaceous material thus creating a severe restriction. Discussions with mine site personnel indicated that some time previously a decision had been made to cease placing a chemical cleaning agent in the water bath. The basis for this decision is unclear; however it has obviously proved to be incorrect.

Figure 5.3
Internal View of Scrubber Tank from PJB 114 at Elouera Colliery

Examination of PJB 132, which had a raw exhaust elemental carbon concentration of 139 mg/m^3 and carbon monoxide of 1,250 ppm, revealed a similar situation to that of PJB 114. Backpressure on the engine arising from the scrubber tank was found to be excessive, however in the interests of time a chemical cleaning agent was dosed into the scrubber tank and the vehicle driven for approximately four hours. At the same time a new fuel pump was fitted and the raw exhaust re-tested.

Elemental carbon dropped from 139 to 46 mg/m^3, carbon monoxide from 1,250 to 690 ppm and backpressure on the engine from approximately 170 kPa to <1 kPa. The vehicle returned to service the same day with minimum loss of availability.

It is clear that these two cases have highlighted the importance of ensuring scrubber tanks are maintained in a clean condition and that a simple backpressure test would have highlighted the issue.

The availability of the mobile gas laboratory and the R&P Series 5100 diesel particulate analyser greatly assisted the diagnostic process.

Investigation of the other vehicles with unacceptable exhaust emissions resulted in the following outcomes:

- Ram Car 194 – The engine in this unit has been found to have many hours of operation under high load (>6,000 hours). The fuel injectors were changed and the unit re-tested, with a resultant raw exhaust elemental carbon concentration of 71 mg/m^3. Site engineering personnel did not consider it worthwhile progressing the matter beyond this point as the vehicle is scheduled to be scrapped in 2004 as the mine approaches closure. Nevertheless the process of replacing the injectors reduced the raw exhaust elemental concentration by over 55%. It is also interesting to note that the raw exhaust carbon monoxide concentration was reduced by 140 ppm by this basic maintenance procedure.

- PJB 103 – Investigation of maintenance records established that this engine had been a reconditioned spare left over after the closure of Tower Colliery. It is understood that the tappets were found to be incorrectly set upon the vehicle's arrival at Dendrobium Mine and site engineering personnel thought that this may have caused permanent damage. As a first step, mine site personnel changed the injectors, cleaned the scrubber tank and air intake system. The engine was re-tested with a resultant elemental carbon concentration of 61 mg/m^3, which is below the 95% UCL for KIA engines. The raw exhaust carbon monoxide concentration was also reduced by 305 ppm.

- SMV 5073 – A review of the history of the vehicle indicated that the unit had been purchased "second hand" from Queensland. This unit, together with SMV 5100 and MPV 98 have been scheduled for investigative maintenance, however to date operational requirements have delayed this process.

5.7.3 Comparison to MSHA Certification Data

Direct comparison of the data collected during this project to that posted by MSHA for approved engines is difficult due to the differences in test methods (torque stall versus ISO 8178), analytical techniques (gravimetric versus elemental carbon) and engine packages.

Nevertheless, some value can be demonstrated by the comparison of MSHA data for Caterpillar 3304 PCNA and 3306 PCNA engines to that obtained in this exercise (Table 5.9). It should be noted that the Illawarra Coal results are an average value for those engines tested and the diesel particulate value is calculated using the conversion EC ≡ 50% DP (ACGIH 2000, 2002).

Table 5.9
Comparison of MSHA and BHP Billiton Illawarra Coal Diesel Particulate Data

	MSHA		BHP Billiton Illawarra Coal			
Engine	DP g/kWhr	DP g/hr	EC g/kWhr	EC g/hr	DP g/kWhr	DPg/hr
Cat 3304	0.64	25.49	0.13	8.5	0.26	17.0
Cat 3306	0.66	39.08	0.09	3.1	0.18	6.2

A review of the results in Table 5.9 indicates significant differences between the MSHA data and that from BHP Billiton Illawarra Coal vehicles.

Given the potential errors in comparing data collected by such disparate means the process demonstrates that in-service vehicles tested under field conditions are likely to have significantly different exhaust particulate concentrations to those tested under laboratory conditions. These differences need to be evaluated when considering the promulgation of statutory limits.

5.7.4 Comparison to Previous Australian Data

Raw exhaust particulate analysis on engines operating within the Australian underground coal mining industry is limited.

Davies (2000), when validating the R&P Series 5100 diesel particulate analyser, conducted repeat analyses on a limited number of engines at Tower Colliery. Unfortunately, unique engine identification details were not recorded except for eight KIA 6-247 units. While this dilutes the usefulness of the data it does give some insight into a portion of the BHP Billiton Illawarra Coal diesel fleet three to four years ago.

Comparative data from Tower Colliery and the current exercise are provided in Table 5.10. It should be noted that the elemental carbon g/kWhr results for Tower Colliery were calculated from total carbon g/kWhr data using the conversion EC ≡ 0.8 TC (ACGIH 2000, 2002).

Table 5.10
Comparison of Tower Colliery and BHP Billiton Illawarra Coal Data

Engine Type	Tower Colliery EC g/kWhr	BHP Billiton Illawarra Coal EC g/kWhr
Cat 3304	0.11 – 1.0	0.02 – 0.22
Cat 3306	0.10 – 0.72	0.02 – 0.30
KIA 6-247	0.26 – 1.4	0.04 – 0.57
Perkins 1006.6	0.2 – 0.35	0.03 – 0.25

From the results in Table 5.10 a general lower trend can be observed within the current BHP Billiton Illawarra Coal diesel fleet to results on a number of unidentified engines at Tower Colliery in 1999 – 2000. There are several possible reasons for this apparent difference. These are:

1. BHP Billiton Illawarra Coal changed all its operations to Eromanga diesel fuel in July 2002. Eromanga is a low sulphur, low aromatic fuel (<1%). West Cliff Colliery has been using this fuel for a number of years.

   In 1999 – 2000 Tower Colliery was using a low sulphur diesel fuel generated from heating oil. The aromatic content of this fuel was typically 15 – 20%.

2. The introduction of underground diesel test stations at all sites (except Dendrobium) has improved emission levels over that in existence in 1999 – 2000.

3. Davies (2000) was attempting to validate the Series 5100 diesel particulate analyser and thus a range of particulate levels were considered useful. To this end a few engines were induced to provide higher than normal concentrations, however these could not be separated from the data in order to give a more accurate data comparison.

Four unique engines could be identified within the Tower Colliery data that had also been retested in the current exercise (Table 5.11).

Table 5.11
Comparison of Specific Vehicles at Tower Colliery and BHP Billiton Illawarra Coal

Vehicle No.	Engine	OC mg/m^3		TC mg/m^3		EC mg/m^3	
		Tower Colliery	BHP Billiton Illawarra Coal	Tower Colliery	BHP Billiton Illawarra Coal	Tower Colliery	BHP Billiton Illawarra Coal
PJB 108	KIA 6-247	3.4 – 70	12	66 – 245	29	56 – 224	17
PJB 115	KIA 6-247	7 – 33	7.2	160 – 242	58	146 – 209	51
PJB 116	KIA 6-247	8.8 – 26	8.5	141 – 191	51	116 – 177	43
PJB 132	KIA 6-247	9.3 – 34	13	202 – 241	152	178 – 223	139

It is clear that three of the four units have significantly lower raw exhaust elemental carbon levels than they did in 1999 – 2000. The other unit (PJB 132) had levels of the same magnitude, however PJB 132 was found to have a blocked scrubber tank resulting in abnormally high results.

A direct comparison is also available on PJB 115 after maintenance in 1999/2000 and during the current exercise (Table 5.12).

Table 5.12
Comparison of PJB 115 Post Maintenance at Tower Colliery (2000) and Dendrobium Mine (2003)

	OC mg/m^3	TC mg/m^3	EC mg/m^3
Tower (post maintenance)	4.6 – 14	70 – 75	59 – 70
Dendrobium (2003)	7.2	58	51

These results give support to the suggestion that a number of engines tested at Tower Colliery in 1999 – 2000 may have had one or more mechanical faults which resulted in elevated raw exhaust elemental carbon emissions. The results from Dendrobium should represent the optimum possible from that particular engine as all units transferred to Dendrobium (new mine) from other BHP Billiton Illawarra Coal operations were overhauled prior to entering service.

The perceived change in elemental carbon emission generation rates from engines at Tower Colliery in 1999/2000 to those currently within BHP Billiton Illawarra Coal operations has significant importance for any future epidemiological studies. It is clear that over the past three to four years a substantial reduction in emission levels has occurred through better engine performance and the more widespread use of disposable diesel exhaust filters.

5.7.5 Inter-Mine Comparison of Data

A general overview of the data collected in this exercise suggests the levels from West Cliff Colliery are lower than those of the other three operations. Those cases where sufficient results exist for comparison are recorded in Table 5.13.

Table 5.13
Comparison of Engine Elemental Carbon Concentration Vs Mine Site

	Average EC mg/m^3		
	Cat 3304	KIA	Perkins
West Cliff	17.8	17	22.8
Appin	-	-	34.3
Dendrobium	22.6	65.3	-
Elouera	39.7	69.6	-

For each engine type West Cliff Colliery appears to have a lower average raw exhaust elemental carbon concentration, however limited data restricts the ability for statistical analysis. However, analysis of variance (ANOVA) data for the Cat 3304 engine rejected the mean hypothesis for West Cliff, Dendrobium and Elouera but not when ANOVA was conducted just for West Cliff and Dendrobium. Similarly for the Perkins 1006.6 engine the mean hypothesis using ANOVA was not rejected for West Cliff and Appin. Insufficient samples existed at West Cliff to perform ANOVA on the KIA engine. Details of the ANOVA are provided in Table 5.14.

Table 5.14
ANOVA of Raw Exhaust Elemental Carbon Concentration for Engine Type and Mine Site

Engine Type	Mine	Null Hypothesis	F Test Statistic	F Critical Value $\alpha_{0.05}$
Cat 3304	West Cliff / Dendrobium / Elouera	Rejected	3.98	3.89
Cat 3304	West Cliff / Elouera	Rejected	7.417	4.96
Cat 3304	West Cliff / Dendrobium	Not Rejected	0.03224	7.71
Perkins 1006.6	West Cliff / Appin	Not Rejected	0.32	4.84

In each case if $F_{Test\ Statistic} > F_{Critical\ Value}$ then the null hypothesis (H_0) that there is no significant difference in the means of the raw exhaust elemental carbon concentrations of the same engine types at different operations, is rejected. The alternative hypothesis (H_A) is that there is a significant difference between the mean raw exhaust elemental concentrations for the same engine type at different operations.

In summary, the average elemental carbon levels in the exhaust of Cat 3304 engines from West Cliff and Dendrobium is significantly different to the average from Elouera Cat 3304 engines at the 95% confidence level. No apparent reason appears to exist for this difference.

5.7.6 Influence of Eromanga Fuel

As stated in section 5.7.4, one factor in reducing raw exhaust elemental carbon levels may be the use of Eromanga fuel. To examine this aspect further the results of all engines from West Cliff, which has used Eromanga for 15 years, were compared to the other three mines that have only been using the product since July 2002. The results of this comparison are presented in Table 5.15.

Table 5.15
Comparison of Average Engine Elemental Carbon Concentration Vs Mine Site

Mine	Average Engine EC (g/kWhr)
Appin	0.10
Dendrobium	0.19
Elouera	0.18
West Cliff	0.10

ANOVA of the elemental carbon concentrations (as g/kWhr) resulted in the mean hypothesis being rejected, suggesting that there is a significant difference between engine levels at the four mines tested in this project. When the data from Elouera was removed the null hypothesis (H_0) was not rejected, indicating that the raw exhaust elemental carbon results from engines at Elouera Colliery are significantly different to the other operations.

In this case the null hypothesis (H_0) tested was that there is no significant difference between the raw exhaust elemental carbon concentrations for engines at West Cliff to those at Appin, Dendrobium and Elouera. The alternate hypothesis (H_A) is that there is a significant difference in raw exhaust elemental carbon concentrations for engines at West Cliff to those at Appin, Dendrobium and Elouera. The results of this ANOVA analysis are provided in Table 5.16.

Table 5.16
ANOVA of Raw Exhaust Elemental Carbon Concentration for all Engine Types

Mine	Null Hypothesis	F Test Statistic	F Critical Value $\alpha_{0.05}$
West Cliff, Appin, Dendrobium, Elouera	Rejected	4.155	2.72
West Cliff, Dendrobium, Appin	Not Rejected	2.544	3.18

5.7.7 Relationship Between Raw Exhaust Elemental Carbon Generation Rates and Current Statutory Ventilation Requirements

Within the NSW underground coal mining industry it is a statutory requirement that 0.06 m^3/s/kW of air must be provided in a section where a diesel vehicle is operating.

This value is historically based on the dispersion of gaseous emissions and may not be appropriate for the management of elemental carbon.

Using this value of 0.06 m^3/s, it is possible to calculate for each engine type the concentration of elemental carbon likely to be present in the atmosphere if the minimum current ventilation rate was applied (Table 5.17).

Table 5.17
Predicted Atmospheric Elemental Carbon Concentration (mg/m^3) at NSW Minimum Ventilation Requirements

Engine Type	Average Exhaust EC g/hr	Predicted Atmospheric Concentration at Minimum Statutory Airflow EC mg/m^3
Cat 3304	8.5	0.62
Cat 3306	3.2	0.14
KIA 6-247	12.6	1.16
Perkins 1006.6	11.0	0.73
MWM D916.4	10.1	0.99
MWM D916.6	6.2	0.41

From the calculated values in Table 5.17 it could be anticipated that the current statutory limit of 0.06 m^3/s/kW for each diesel engine would be unlikely to control atmospheric elemental carbon concentrations below the NSW Minerals Council (1999) best practice standard of 0.2 mg/m^3 DP (0.1 mg/m^3 EC).

Conversely, to achieve the goal of 0.1 mg/m^3 elemental carbon in the general airbody, the following air quantities would be required (Table 5.18).

Table 5.18
Quality of Air Required to Reduce Exhaust to 0.1 mg/m^3 Elemental Carbon

Engine Type	Quantity of Air (m^3/s) to Reduce Exhaust to 0.1 mg/m^3 EC
Cat 3304	23.4
Cat 3306	9.0
KIA 6-247	34.8
Perkins 1006.6	30.7
MWM D916.4	27.3
MWM D916.6	17.2

While care should be exercised when interpreting this data (due to the limited dataset and differences in testing), it does serve to highlight that the use of ventilation on its own to control raw exhaust elemental carbon concentrations is impractical in most current NSW coal mines and the use of other control technologies (e.g. exhaust filtration, low emission engines), is required.

5.7.8 Relationship Between Raw Exhaust Gas and Elemental Carbon Concentrations

There is evidence to suggest that raw exhaust gas concentrations are linked to particulate levels (Holz 1960, Waytulonis 1985).

Regression analysis of elemental carbon – carbon monoxide and elemental carbon – oxides of nitrogen, collected during this project, did not indicate any statistically significant relationships (R^2 ranged from 0.05 to 0.77).

This result was found to be surprising given other evidence, however it may merely be an artifact of the sampling procedure adopted in the current exercise.

Individual results on PJB 114 (Tables 5.3 and 5.5) clearly indicate, under free-flow conditions, that when the raw exhaust carbon monoxide level is high the elemental carbon is also generally high (Figure 5.4). This arbitrary relationship may have other complex interconnections which are not apparent from the limited data collected.

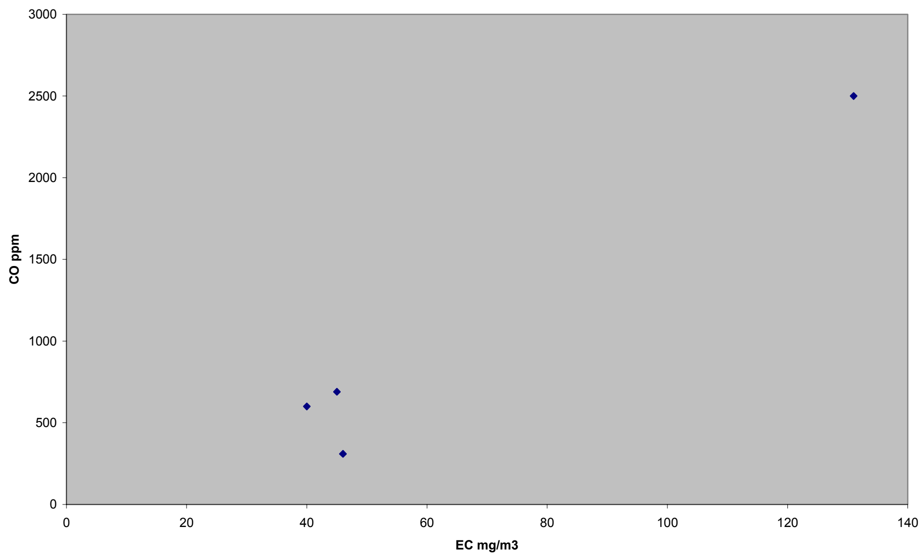


Figure 5.4
Scatter Diagram of Raw Exhaust Carbon Monoxide Concentration Versus Elemental Carbon for PJB 114

5.8 CONCLUSIONS

As a result of a large scale monitoring programme where the raw exhaust of 66 engines currently in service at four BHP Billiton Illawarra Coal mines were tested, it is possible to draw the following conclusions.

- The R&P Series 5100 diesel particulate analyser and a mobile gas laboratory are very effective in identifying engines with abnormal raw exhaust emissions. In the project completed at BHP Billiton Illawarra Coal a total of seven out of 66 in-service engines were deemed to be unacceptable and subjected to further investigation.

Two engines were found to have blocked scrubber tanks, thus restricting exhaust flow and placing a very high backpressure on the engine. Another engine had the injectors changed and the fourth had the injectors changed and the scrubber tank and air intake system cleaned. The remaining three engines are awaiting investigative maintenance when operational conditions allow.

- Comparison of results obtained in the present study to data collected at Tower Colliery in 2000 suggests that a number of units at that time may have had one or more maintenance issues which resulted in high raw exhaust particulate concentrations.

- There is evidence to suggest that current ventilation requirements may not be sufficient to control atmospheric elemental carbon concentrations to below a best practice standard of 0.1 mg/m^3 EC. Other control technologies will be required to ensure a practical solution to the control of raw exhaust emissions is achieved.

- Significant benefits can flow to mine sites by the use of a routine raw exhaust monitoring programme as it allows engines to be tuned to maximum power output while still maintaining control of exhaust emissions.

- An effective maintenance programme will reduce employee exposure to diesel exhaust emissions (gaseous and particulate). As a result of this project BHP Billiton Illawarra Coal has now scheduled into their maintenance programmes the routine testing of vehicle engine exhausts for diesel particulate using the R&P 5100.

6. EFFECT OF ENGINE DESIGN ON DIESEL PARTICULATE CONCENTRATION

6.1 INTRODUCTION

The majority of diesel engines currently in use within the Australian underground coal mining industry represent designs first introduced in excess of 20 years ago. In the last 10 years environmental regulatory authorities, both in Europe and the USA, have focused on the reduction of diesel emissions from over-the-road diesel engines and more recently, non-road engines.

While this process continues to gain momentum and engine design requirements become more stringent, low emission electronically controlled engines have been available for some time but their introduction to the underground coal mining industry has been restricted due to intrinsic safety requirements. Waytulonis (1992) demonstrated that such an engine could provide a reduction in particulate generation of up to 50% over that produced by engines typically used within the coal industry.

More recently Bagley et al (2002) reported reductions of up to 60% in total and elemental carbon when new generation electronic controlled engines were compared to naturally aspirated engines operating under the same conditions. Moreover, there was no evidence of increased production of nanoparticles with the use of low emission engines. Also the polynuclear aromatic hydrocarbon and biological (mutagenic) activity levels also showed large decreases with use of electronically controlled engines (by up to about 90% and 65% respectively).

The substantial benefits of newer designed engines (albeit not electronically controlled), has been demonstrated by Davies (2000) who compared the emissions from mine transport vehicles to that of commercial over-the-road vehicles.

In this case a KIA (6-247) diesel engine (50 kW) was compared with a Toyota Landcruiser Series 75 engine (95 kW) with the total carbon output of the KIA engine ranging from 0.33-1.7 g/kWh to 0.005-0.09 g/kWhr for the Toyota engine.

While Davies (2000) acknowledges that such direct comparisons in the field are difficult due to the different engine system used in mine vehicles, it is not difficult to imagine that newer, more fuel efficient, design engines will offer substantial benefits in emission reduction.

This also appears to be the view of the European Union and US EPA who now require engine manufacturers to introduce new technology engines on a tiered scale.

For heavy duty highway engines the US EPA requires particulate matter generation to not exceed 0.01 g/bhp-hr (0.013 g/kWhr) for all engines produced after 2007 (US EPA 2000) Non-road engines (generators, etc) have been treated more leniently but are still required to meet new, more stringent, standards.

In 2002 the engine manufacturer Caterpillar Inc, reacted to impending requirements on diesel particulate generation by ceasing production of older design engines (Cat 3304 and 3306). This has a substantial influence on the Australian underground coal mining industry as these engines make up 51.5% of the NSW underground diesel fleet (NSW Department of Mineral Resources, 2001), which would be indicative of the total Australian diesel fleet. As a result of this action there is an expectation that the characteristics of the Australian coal industry underground diesel fleet will change over the next 10 years as older units are replaced. What is unclear is the effect that this change will have on workplace atmospheric diesel particulate levels in underground coal mines.

6.2 AIM OF PROJECT

Historically, the benefits of newer generation engines within the Australian coal industry, have only been able to be evaluated under laboratory conditions due to issues of intrinsic safety with newer design engines. Direct comparisons under similar operations have not generally been possible, however a major project investigating fire-protected vehicles (Pratt 2003) presented a rare opportunity to quantify the potential reduction in diesel particulate being released into a mine atmosphere from a newer engine design.

The project aim was to establish if the introduction of fire-protected vehicles, intended to transport personnel underground, will significantly reduce the level of diesel particulate in the mine atmosphere in respect to that experienced with current personnel transportation vehicles.

6.3 HISTORICAL OVERVIEW

Within the underground mining industry the issue of engine design in relation to emission generation was most probably first raised by Holz (1960) who indicated that the results of approval tests of engines suggested that the design of the combustion chamber and the fuel-spray characteristics both affected exhaust emissions.

Although the focus of Holz (1960) was on gaseous emissions rather than particulate, it is interesting to note that he concluded the maximum concentration of oxides of nitrogen was usually greater in the exhaust of direct-injection engines compared to indirect-injection engines. He also concluded that high pressure supercharging or turbocharging appeared to increase the maximum concentration in the exhaust of any diesel engine.

The issue of engine design was further discussed in 1977 at a workshop on the use of diesel equipment in underground coal mines (NIOSH 1982). The workshop concluded:

> *"Diesels used in mining machinery are predominantly indirect injection, naturally aspirated, four-cycle engines. This is because such engines currently have more favorable emissions characteristics, thereby resulting in lower ventilation requirements. This type of engine is likely to retain these advantages for the next few years."*

The workshop also made the following recommendation:

> *"Further studies are recommended to characterise and compare engine types and those emissions which are thought to have the most adverse health effects, especially NO_2, particulate, and PNA's."*

The conclusion that naturally aspirated indirect injection engines would be used for the "next few years" has turned out to be very profound, with the NSW coal mining industry underground diesel fleet still dominated with this design some 25 years later.

6.4 ENGINE DESIGN RESEARCH

6.4.1 Over-The-Road Diesel Engines

Following the publication in the US in 1991 that all diesel engines meet a particulate matter emission standard, major engine manufacturers identified measures by which these requirements could be achieved. Some areas of investigation have been:

- Improved fuel injection techniques
- Improved air management methods

- Improved combustion chamber design
- Improved oil control

Improvements arising from these investigations have resulted in major manufacturers signaling their ability to meet a US EPA particulate matter requirement of 0.01 g/bhp-hr (0.013 g/kWhr) for all engines produced after 2007.

The development of these new generation engines has brought a new set of issues predominantly focused on the generation of ultrafine or nanoparticles, which it was considered could give rise to increased adverse health effects compared to particulates from older generation engines (Seaton 1995, Bagley et al 1996).

An excellent overview of the issue in respect to nanoparticle generation from diesel engines is provided by Kittelson (2001). He concludes that in new generation engines a significant amount of particulate matter (eg 90% of the number and 30% of the mass) is formed during exhaust dilution from particle precursors that are in the vapour phase in the exhaust pipe. Thus engines with low carbon mass emissions may have high number emissions of volatile but not solid particles. He also concludes that nanoparticle measurements are strongly influenced by the sampling and dilution techniques employed.

Kittelson's conclusions seem to be borne out by Bagley et al (2002) who conducted a major study in a US underground salt mine. In this study comparisons were made between naturally aspirated engines and new generation electronic controlled engines, and major decreases (60%) were found in total and elemental carbon when electronically controlled engines were used.

Moreover, there was no evidence of increased production of nanoparticles with the use of low emission engines. Also the PAH and biological (mutagenic) activity levels also showed large decreases with use of the electronically controlled diesel engines (by up to about 90% and 65%, respectively).

For the underground mining industry this study significantly reduces concerns that the introduction of new generation over-the-road design engines would merely replace one problem with another.

6.4.2 Underground Mining Diesel Engines

Research into new technology engines for the underground mining industry has not been as pronounced as the over-the-road diesel engine industry. This is due mainly to a small market and the lack of the same regulatory pressures as the over-the-road industry. In essence, whatever is developed for the large over-the-road industry will inevitably flow on to the underground mining industry. This process is well under way within the metalliferous industry with electronic controlled engines being in use for a number of years. The same cannot be said for the underground coal industry where newer generation engines are just starting to come on the horizon. This is especially the case within Australia where the Caterpillar 3126 engine is only now gaining acceptance.

Notwithstanding the above, considerable effort has been expended within the underground mining industry in recent years to demonstrate the benefits of newer design engines. Waytulonis (1992) reported on research at the US Bureau of Mines where the emissions from a normally aspirated diesel engine (Caterpillar 3304) of 1979 vintage were compared with a 1991 electronically controlled engine (DDC 8V-92 TA). Tests were conducted on a dynamometer at various peak torques (PT) and rated power (RP) settings (Table 6.1).

Table 6.1

Comparison of Exhaust Emissions From New & Older Design Engines

Engine	Contaminant	PT50	PT75	PT100	R50	R75	R100	Average
Detroit Diesel 8V-92TA	NO_x g/kWhr Particulates g/kWhr	7.16 0.07	7.54 0.075	10.57 0.084	4.96 0.07	5.06 0.055	6.33 0.055	6.93 0.070
Caterpillar 3304 PCNA	NO_x g/kWhr Particulates g/kWhr	12.60 0.23	8.28 0.12	4.05 0.70	12.48 0.84	9.30 0.31	5.19 0.21	8.66 0.40

What makes this comparison more impressive is the fact that the DDC 8V-92TA engine is 298.3 kW compared to 74.6 kW for the Caterpillar 3304 PCNA engine and that the results for the DDC engine were generated using a fuel with a sulphur content of 0.1% w/w versus 0.04% w/w for those results generated from the 3304 PCNA engine. It is clear from these results that the DDC 8V-92TA engine is much cleaner than the Caterpillar 3304 PCNA engine typically used in Australian underground coal mines.

Grenier and Gangal (1993) evaluated the level of airborne emissions from an electronically controlled engine under mining conditions. In this project a Detroit Diesel 6V-92TA DDEC engine, installed in a Jarvis Clark haulage truck, was evaluated under haul and dump duty cycles under two different load requirements. Stationary sampling systems were established at the intake and exhaust points of the section of mine the vehicle was operating and measurements made for carbon monoxide, nitric oxide, nitrogen dioxide, sulphur dioxide and respirable combustible dust.

The conclusions from this study were that under the operating conditions of the test, concentrations of all measured contaminants remained well below the recommended worker exposure limits. No visible smoke was observed upon acceleration or on engine start-up.

In regard to engines used in the underground mining industry, an excellent comparison in regard to particulate generation is provided by the US Mine Safety and Health Administration (MSHA) via their “Particulate Index” for approved engines.

Under the MSHA index each engine undergoing the approval process is tested on a dynamometer and from the exhaust analysis MSHA determines the air quality necessary for dilution of the diesel particulate matter (measured gravimetricaly) to 1 mg/m^3. Under these laboratory test conditions a lower particulate index is indicative of an engine with lower particulate matter emissions. These results are published on the MSHA website together with the particulate matter results in g/hr and g/bhp-hr.

Unfortunately this information has limited use within the Australian coal mining industry as none of the newer generation engines listed by MSHA are currently approved for use in NSW underground coal mines. Notwithstanding the above, it is interesting if a comparison is made between an engine commonly in use within Australian coal mines (Caterpillar 3306) and a new generation engine (Table 6.2).

Table 6.2
MSHA Particulate Index Data for Older & New Generation Engines

Engine	Rated Power (kW)	PI (m^3/s)	DP (g/kW-hr)
Caterpillar 3306 PCNA	112	12.74	0.71
Detroit Diesel Series 50 DDEC	235	2.36	0.07

Given that the NSW Minerals Council (1999) recommends a best practice workplace exposure standard of 0.2 mg/m^3 (measured as DP), the MSHA particulate index values would equate to 63.7 m^3/s for the 3306 engine and 11.8 m^3/s for the DDEC.

As the current minimum statutory ventilation rate for a Caterpillar 3306 PCNA engine is approximately 6.7 m^3/s (based on the requirement of 0.06 m^3/s/kW), it is doubtful that Australian operations could ever achieve the ventilation requirement prescribed by the MSHA process (especially when ventilation rates are additive for each individual engine). Newer generation engines would provide some opportunity to achieve MSHA ventilation requirements especially with lower power new generation engines instead of those indicated in Table 6.2.

From the above example it is clear that although newer generation engines bring significant benefit in reduced particulate generation, other control technologies may still be required if best practice workplace exposure standards are to be achieved.

6.5 METHODOLOGY AND TECHNIQUES

6.5.1 Introduction

The goal of the research detailed herein was to build on the initial work of Davies (2000) and attempt to make more precise emission comparisons, under mining conditions, between current transportation vehicles and a prototype transportation vehicle fitted with a newer design engine. As part of this exercise, techniques discussed in sections 2.4 and 3.2 of this thesis were utilised.

6.5.2 Test Methods

In association with BHP Billiton Illawarra Coal, who were undertaking a research project funded by the Australian Coal Association (Pratt 2003) to demonstrate the suitability of fire-protected 4WD vehicles to operate in underground NSW coal mines, the opportunity presented to compare a newer design engine to current mine engines under the same operating conditions.

Given this unique opportunity, a range of measurements were made using the equipment and methods as per Table 6.3. This project was conducted at Elouera Colliery.

Table 6.3
List of Monitoring Methods/Equipment For Vehicle Comparison Project

Issue	Method/Equipment
Atmospheric DP Concentrations	NIOSH Method 5040
Atmospheric Gas Concentrations (CO, NO, NO_2)	Quest Multilog 2000 Portable Gas Analyser
Raw Exhaust DP Concentrations	R&P Series 5100 DP Analyser

In all cases the equipment was calibrated in accordance with either manufacturer's recommendations or the National Association of Testing Authorities guidelines (NATA 2000). Where possible all data was logged for future evaluation.

6.5.3 Sample Collection Protocol

All sampling at Elouera Colliery was undertaken over a 1.8 km section of roadway from the mine portal to a point where height restriction issues made it impossible for the 4WD fire-protected vehicle (Figure 6.1) to travel any further into the mine. Comparisons were made to current NSW Department of Mineral Resources approved flameproof transportation vehicles (Figure 6.2). Three separate flameproof vehicles were tested in order to ensure any bias due to age or maintenance condition was minimised.

Figure 6.1
ACARP Project C6042 Prototype Fire-Protected Vehicle

Figure 6.2
Current Mine Flameproof Vehicle

The selected section of roadway provided a useful test venue as it required several stops for section lights and included a steep incline between coal seams. All vehicles were driven by the same operator following normal mine operating procedures and all vehicles operated on the same fuel supply. A standard driving schedule was devised to simulate a vehicle undertaking delivery duties within a section of the mine. Testing for ambient contaminants was performed while vehicles were driven to the above schedule.

This process was repeated over a period of approximately 10 days until sufficient samples were collected.

6.6 EXPERIMENTAL RESULTS

The raw exhaust of the 4WD prototype vehicle and three current transportation vehicles was analysed for diesel particulate at torque stall conditions using the R&P 5100 DP analyser. The results are presented in Table 6.4.

Table 6.4
Raw Exhaust Analysis – Diesel Particulate

Vehicle	Engine	Rated Power (kW)	Organic Carbon (mg/m^3)	Total Carbon (mg/m^3)	Elemental Carbon (mg/m^3)	Elemental Carbon (g/kWhr)
4WD Prototype	Toyota 1 Hz (OHC-PCNA)	95	4.7	11.4	6.7	0.02
Unit No. 114	KIA 6-247	50	5.1	26.4	21.3	0.11
Unit No. 133	KIA 6-247	50	8.6	30.0	21.4	0.11
Unit No. 327	KIA 6-247 (supercharged)	70	6.7	22.3	15.6	0.06

Gaseous emissions in the raw exhaust were also measured under torque stall conditions, the results of which are presented in Table 6.5.

Table 6.5
Raw Exhaust Analysis – Gaseous Emissions

Vehicle	CO ppm	NO_x ppm	CO_2 %
4WD Prototype	320	500	6.5
Unit No. 114	1,450	260	11.5
Unit No. 133	530	270	11.0
Unit No. 327	220	350	10.5

Sampling for atmospheric DP concentrations was conducted inside the driver's cabin of all four vehicles using SKC disposable sampling heads. The results provided in Table 6.6 are the average of at least two samples collected at the same time.

Table 6.6
Ambient Diesel Particulate Concentrations Inside Driver's Cabin of Vehicles

Vehicle	Organic Carbon (µg/m^3)	Elemental Carbon (µg/m^3)	Total Carbon (µg/m^3)
4WD Prototype	223	19	242
Unit No. 114	169	183	345
Unit No. 133	224	123	367
Unit No. 327	284	58	342

Sampling for ambient gaseous concentrations was also performed in the driver's cabin of all four vehicles. Peak concentration values for all contaminants tested are presented in Table 6.7.

Table 6.7
Ambient Gas Concentrations (Peak Values) Inside Driver's Cabin of Vehicles

Vehicle	CO ppm	NO ppm	NO_2 ppm
4WD Prototype	5	2.5	Not detected
Unit No. 114	34	3.5	Not detected
Unit No. 133	7	4.2	Not detected
Unit No. 327	8	8.8	Not detected

6.7 DISCUSSION OF RESULTS

Examination of the results in Table 6.4 clearly indicates that the raw exhaust elemental carbon levels generated by the Toyota 1 Hz engine (0.02 g/kWhr) are substantially lower than that generated by all KIA 6-247 engines (0.06 – 0.11 g/kWhr). This conclusion needs to be considered with a level of caution as the 4WD prototype vehicle did not have an exhaust system similar to that on the KIA vehicles. The 4WD prototype achieved compliance with statutory temperature requirements (150°C) by the injection of water into the exhaust immediately below the exhaust manifold. The KIA engine vehicles were fitted with a standard water bath which may place increased backpressure on the engine.

Nevertheless, there is sufficient evidence to suggest that the 4WD prototype vehicle is discharging a lower level of elemental carbon into the general mine atmosphere. This conclusion is strongly supported by the results of ambient monitoring in the driver's cabin of all vehicles (Table 6.6).

These results indicate that the atmospheric elemental carbon concentrations within the driver's cabin of the 4WD prototype vehicle (19 $\mu g/m^3$) are significantly below that within the driver's cabin of the KIA engine vehicles (58 – 183 $\mu g/m^3$). This represents a reduction of between 67 – 90% dependent on the engine involved.

The peak ambient gaseous concentrations do not appear to show any distinctive difference for carbon monoxide between the 4WD prototype vehicle and two of the KIA engine units. The third unit (No. 114) had a major carbon monoxide peak which is consistent with the high concentration of carbon monoxide in the raw exhaust (1,450 ppm).

On the positive side, this level of carbon monoxide was present for only about 3-4 minutes (Figure 6.3) which is the approximate time taken to traverse the incline between coal seams, suggesting that a “plug” of exhaust was travelling at the same speed as the vehicle. Attempts to repeat this condition were unsuccessful, with the highest subsequent carbon monoxide level recorded being 12 ppm and levels during the rest of the monitoring exercise (several hours) were typically below 5 ppm.

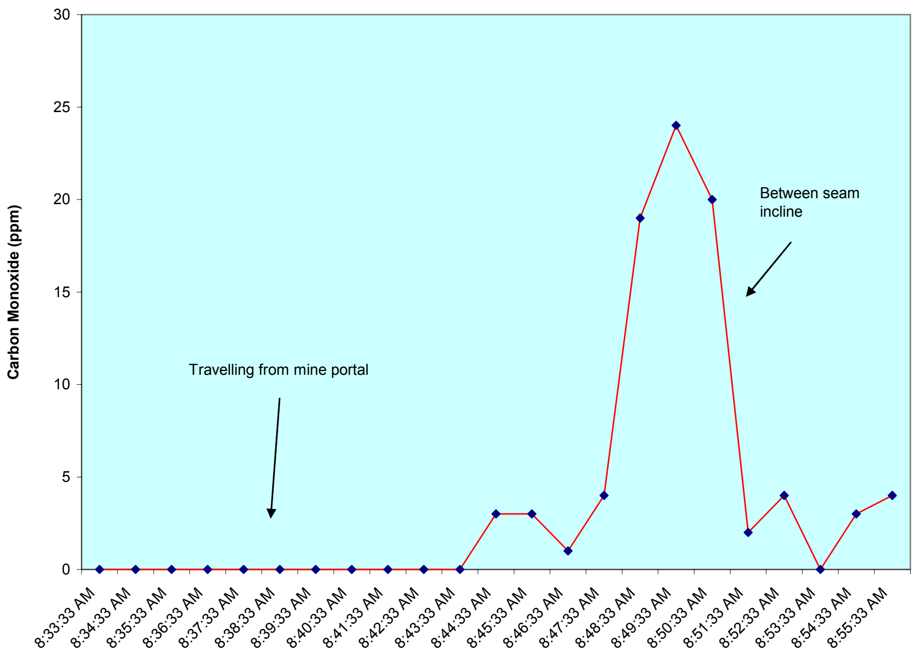


Figure 6.3
Quest MultiLog 2000 Graph of Carbon Monoxide Concentrations – Unit No. 114

The ambient peak concentrations for nitric oxide did not appear to display any relationship to the raw exhaust concentrations, with the vehicle with the lowest raw exhaust oxides of nitrogen level (4WD prototype) having the lowest ambient concentration.

6.8 CONCLUSIONS

Over the last 10 years emissions from engines produced for over-the-road diesel vehicles have reduced significantly.

Unfortunately, this major advance has not transferred to the Australian underground coal mining industry due to the market size, intrinsic safety issues and mine engineer preference.

While the benefits of new technology engines have been known for some time, little data exists to demonstrate the benefits of this advance in technology over the engines currently used within the Australian coal mining industry. The data generated within this project demonstrated that under mining conditions an engine of newer design has the potential to reduce atmospheric elemental carbon concentrations by up to 67 – 90%. Similarly, raw exhaust elemental carbon analysis indicates similar significant reductions.

While these results are encouraging, the true situation will not be clear until a new technology engine (eg electronic controlled) passes intrinsic safety approvals and is fitted to a normal underground vehicle. Comparisons between vehicles of this type and current mine vehicles, using principles similar to that described above, will be very useful. The data generated from the current research project suggests that such a process will produce positive benefits and is worthy of pursuing.

7. TOWER COLLIERY RESEARCH GROUP EXPOSURE DATA

7.1 INTRODUCTION

The publication in 1988 of Criteria Bulletin No. 50 (NIOSH 1988) gave rise to concern within BHP Steel Division Collieries (the precursor to BHP Billiton Illawarra Coal) as to potential health issues associated with exposure to diesel particulate. After a preliminary review (Gliksman and Davies 1989) a Research Group was established and amongst other duties tasked with establishing the level of employee exposure to diesel particulate.

As no data existed within the Australian mining community as to levels of worker exposure to diesel particulate, the Research Group decided to use the techniques developed by the US Bureau of Mines and the University of Minnesota (Cantrell and Rubow 1991, 1992) to develop an employee exposure profile at a modern underground coal mine – Tower Colliery.

During the period 21 August 1990 and 20 December 1994 in excess of 400 full shift personal diesel particulate samples were collected at Tower and eight other NSW collieries. Limited sampling was performed post 1994 in several Queensland mines, as the result of a Joint Coal Board Health & Safety Trust project which later led to a major study on the suitability of NIOSH Method 5040 in underground coal mines (Rogers and Whelan 1996).

At the same time as the employee exposure profile was being established, the Tower Colliery Research Group was evaluating a number of control technologies. Much of this research formed the basis of many of the processes currently in place to control diesel particulate emissions in the Australian underground coal mining industry. In all, some 752 diesel particulate samples were collected by the Tower Colliery Diesel Research Group.

Discussions with members of the Tower Colliery Research Group indicate that while a number of decisions were based on the best available data, time constraints and limited resources did not allow for the full scientific evaluation of the data that was collected.

The data held within BHP Billiton Illawarra Coal represents a major proportion of that for the Australian underground coal mining industry and thus continues to be used to guide mine operators in their actions to control particulate levels arising from diesel engines used underground.

7.2 AIM OF PROJECT

In the first instance the aim of the project is to review all the data from nine NSW and one Queensland coal mines and if possible assign each result to distinctive "Homogeneous Exposure Groups" (HEGs). Once completed, this data would be analysed using the principles of occupational exposure assessment so that comparisons of the various HEGs can be made. Such a process may identify areas previously not considered as requiring control.

The second stage of the project would investigate the effectiveness of the various control technologies evaluated by the Tower Colliery Research Group using appropriate statistical procedures.

The final stage of the project aims at establishing the correlation between equipment design and operator exposure, irrespective of the characteristics of the mine where vehicles of the same type are being used. If established, this outcome would demonstrate that engine output overrides other factors in terms of contributing to employee exposures.

7.3 TOWER COLLIERY DIESEL RESEARCH GROUP

7.3.1 Background

In 1990 BHP Steel Division Collieries established a research group at Tower Colliery (approximately 80 km south-west of Sydney) to investigate the issue of diesel particulate and recommend an appropriate course of action. Membership consisted of the mine manager, mine engineer, divisional engineer, a representative of the workforce and external specialists in aerosol sampling, fuel quality and occupational hygiene.

At an early date the committee took the view that the lack of any exposure data for diesel particulate in the Australian coal mining industry was an impediment to developing effective control technologies. The Research Group also concluded (Tower 1993) that the techniques developed by the US Bureau of Mines (Cantrell 1991) were the most appropriate to collect typical exposure data.

In the initial stages of the sampling exercise, the Research Group took the view that any data that could be collected would be useful and thus a non targeted approach to sampling was adopted.

Following a review of the early data collected, the Research Group decided that a more formal approach to sampling was required, which targeted every task in the mine that had some diesel activity as a component. Consequently a sampling matrix was developed (Table 7.1) and all samples were collected in accordance with its format.

Table 7.1
Sampling Matrix Used at Tower Colliery

Job Location	Driver	General Hand	Fitter	Deputy
Pit Bottom	Atmosphere testing	Material handling	Diesel maintenance	Atmosphere testing
Transport Road	Hanging cables and pipes (Domino) Material transport (MPV) Personnel transport (PJB) Cleaning and grading (Myne grader) Towing Powertram (Bagshaw)	Material handling Hanging cables and pipes Towing Powertram	Diesel maintenance Other	
Panel	Belt installation (Domino) Moving boot end (Eimco) Moving fan (Domino) Hanging cables and pipes (Domino)	Hanging cables and pipes Miner driver Shuttle car driver Cable man Material handling	Diesel maintenance Other	
Cut Through	Mucking out (Bagshaw) (Eimco) (Bobcat) (Domino)	Material handling	Diesel maintenance Other	
Return	Mucking out (as above)	Material handling		
LW		Shearer operator Chock man	Diesel maintenance Other	
LW Move	Installing tailgate drive (Eimco) Moving boot end (Eimco) Moving chocks (Eimco, Noyes)	Chock removal Chock installation Material handling	Diesel maintenance Other	
Belt Road	Mucking out (Bobcat)	Cleaning		

Between 21 August 1990 and 16 February 1993 some 204 personal diesel aerosol particulate samples were collected at Tower Colliery in accordance with the sampling matrix described above (Tower 1993). All samples were collected while the mine was operating on normal diesel fuel that conformed to statutory requirements.

Unfortunately, it is impossible to establish from the available records if all categories in the matrix were sampled. This is mainly due to poor or confusing identification notes on work sheets but it appears many of the activities for the driver and general hand were sampled. The same cannot be clearly stated for the fitter and deputy.

Following the collection of the data between 1990 – 1993 at Tower Colliery, BHP Steel Division Collieries sought funding from the Australian Coal Association Research Programme (ACARP) to investigate several promising control technologies (Pratt et al 1995).

As part of this project worker exposures were evaluated at eight NSW underground coal mines with diesel activities sufficiently different to Tower Colliery.

Consequently, the Research Group finalised a list of operations that appeared to meet all the predetermined criteria. The split up of these operations in terms of coalfield location is indicted in Table 7.2.

Table 7.2
Location of Mines For Testing

Location	No. of Mines
Northern Coalfield	2
Western Coalfield	2
Southern Coalfield	4

One operation similar to Tower Colliery was included in the operations to be sampled as a comparison.

Sampling was undertaken at the eight collieries in the period 5 July 1994 to 20 December 1994, with the aim of obtaining a minimum of six full shifts of operational sampling. In most cases this was achieved, however operational conditions shortened several sampling schedules and extended others.

A total of 134 personal samples were collected at the eight collieries during the sampling period.

In 1997 the Research Group assisted a Joint Coal Board Health & Safety Trust project by sampling worker exposures at a mine in Central Queensland. A total of 16 samples were collected, mainly during a longwall change-out.

Numerous follow-up samples were collected at Tower Colliery over the period 1994 – 1997, resulting in a total of 407 personal exposure samples (Appendix 1).

In the period 1994 – 1995 considerable testing of various control technologies took place in a test tunnel (Figure 7.1) at Tower Colliery. Initially, this tunnel was fabricated on the surface from steel formwork and brattice but after about a year a section of roadway underground was dedicated to the project. Initially, tests needed to be carried out on the surface due to approval and/or safety issues with some of the technologies being evaluated.

Figure 7.1
Tower Colliery Surface Test Tunnel

From the available records a total of 345 diesel particulate samples were collected under various operating conditions (Appendix 2). Many of these samples were collected in the breathing zone of the vehicle operator, while a smaller proportion were static samplers along the length of the tunnel.

In all, 752 diesel particulate samples were collected by the Tower Colliery Diesel Research Group during the period 1990 – 1997.

7.3.2 Overview of Available Data

Although 752 diesel particulate samples were collected by the Tower Colliery Diesel Research Group, the usefulness of this data was compromised in the current exercise by a lack of clear identification of job tasks and vehicle number. This data wasn't considered important for the original sampling exercise and thus was only collected on an ad hoc basis.

As Tower Colliery closed on 20 December 2002 a major effort was made in the period leading up to the closure to obtain all available records.

In some cases this included sampling worksheets which were individually reviewed and correlated with available diesel particulate results to establish the identification of any vehicles working in the area of exposed employees. A level of success was achieved via this laborious process, however many results could not be linked to specific vehicles or engine types.

The importance of this data to the Australian underground coal mining industry cannot be understated. In 1995 it was used to guide the industry to publish the first booklet on the control of diesel particulate (NSW Minerals Council 1996). In 1999 this booklet was updated (NSW Minerals Council 1999) and a booklet was produced by the NSW Joint Coal Board (1999) using the data of Tower Colliery and other groups as the basis for many decisions on control technologies and a best practice workplace exposure standard of 0.2 mg/m^3 (NSW Minerals Council 1999)

All samples were collected using the techniques proposed by Cantrell and Rubow (1991) and all analysis was performed using gravimetric techniques. Consequently, all results are recorded as mg/m^3 diesel particulate (DP) and no subsequent analysis for elemental carbon was undertaken.

7.3.3 Conclusions of Tower Colliery Diesel Research Group

In relation to employee exposure data the Tower Colliery Diesel Research Group concluded in their 1995 publication (Pratt et al 1995) the following.

"• *Personal diesel particulate exposure levels of underground employees at Tower Colliery range from 0.05 to 2.2 mg/m^3. Of the 204 samples collected, 203 are in the range 0.05 to 0.60 mg/m^3.*

Electron microscopy studies indicate these samples represent true diesel aerosol particulate exposure with interference from very fine mine dust being less than 10%, provided that the statutory respirable coal dust standard (3 mg/m^3) is not exceeded. The remaining sample (2.2 mg/m^3) was subjected to electron microscopy to establish if it was in fact diesel particulate. The results of this examination indicated that this sample contained a majority of large limestone particulates consistent with roadway stone dust.

- *The employee exposure data collected at eight NSW underground mines is consistent with previous data collected at Tower Colliery. Exposure levels reflect the level of diesel activity and engine load with the higher exposures occurring during longwall change-out operations.*
- *High dust levels, as found in some operations, can cause overloading of the diesel aerosol particulate sampler, leading to false high exposures being recorded. Electron microscopy has proved to be invaluable as a confirmatory technique in order to ensure that the particles collected are actually composed of a majority of diesel aerosol particulates."*

In regard to potential control technologies the Research Group concluded the following.

"• *Sampling of the operator of a diesel vehicle for personal exposure to diesel aerosol particulates pre and post cleaning of the water-filled scrubber tank does not indicate that the level of cleanliness of the internal surfaces of the scrubber tank is a major factor in reducing diesel aerosol particulates.*

It is more likely that the presence of a physical impaction barrier (eg water), is the major factor in reducing diesel aerosol particulates as observed in research both in Australia and overseas.

Little effect was observed when using a new versus a used intake air filter in terms of diesel aerosol particulate generation except when they become completely blocked.

- *The use of disposable exhaust filter systems fitted to the diesel vehicle after the scrubber tank have been demonstrated to be highly effective in reducing employee exposure to diesel aerosol particulates. Trials indicated reductions of up to 78% for one shift and from between 54 – 78% for up to three shifts operation on a caterpillar 3306 turbo-charged engine.*

  There is a strong possibility that a commercial version of this device could provide the best short term means of controlling diesel aerosol particulates from heavy haulage vehicles.

- *The chemical decoking of engines has been shown to have a positive effect in reducing the generation of diesel aerosol particulates for periods of up to ten months with no observable detrimental effect on engine components.*

  One potential problem is the generation of copious quantities of diesel particulate (soot) immediately after the decoking process, which requires careful management procedures to ensure this exhaust is not released into the general airbody.

- *The existence of a relationship between diesel aerosol particulate and increasing airflow has been established for two vehicles currently used at Tower Colliery. The existence of a uniform relationship to cover all vehicles in any underground mine is more tenuous and would need considerable research. There is no doubt that the issue of ventilation is complex and can be influenced by operating conditions (eg multiple vehicles) and thus empirical calculation of ventilation rates should not be used as the sole means of controlling diesel emissions (especially particulate matter).”*

In the period since 1995, disposable diesel exhaust filters have become the most effective method of a series of technologies for controlling employee exposure to diesel particulate, especially by BHP Billiton Illawarra Coal.

7.4 EXPOSURE ASSESSMENT

7.4.1 Brief History of Exposure Assessment

The issue of occupational exposure to contaminants has given rise to concern by occupational health and safety professionals for centuries, however the evaluation and assessment of these exposures were largely unresolved until the 20th century.

An early list of exposure standards was published in 1928 for gases and vapours (Zangger 1928). This list was extended and resulted in the first statutory list of exposure standards in 1937 with a table of “Maximum Allowable Concentrations” (Bowditch 1937).

In the period from 1937 to the early 1970’s use of exposure standards was based on the prevention of harm to the industrial worker. It was in this period that the American Conference of Governmental Industrial Hygienists (ACGIH) published their first list of maximum allowable concentrations in 1946 and their first list of threshold limit values in 1948 (ACGIH 1984).

With the introduction of the Occupational Health and Safety Act in the USA in 1970, the focus changed from recommendation to one of legal compliance. When formulating the initial employee exposure monitoring requirements in 1974, NIOSH recognised an obligation to make available to employers and occupational hygienists, an informative technical publication detailing ways by which employers could meet their obligations.

This resulted in the publication of an Occupational Exposure Sampling Strategy Manual (NIOSH 1977).

The NIOSH Sampling Strategy Manual introduced the concept of random sampling of a group of workers who have a similar expected exposure risk, commonly called a Homogeneous Exposure Group or HEG. A statistical approach to exposure compliance was also developed based in part on work by Oldham (1953) who noted that the distribution of randomly collected dust measurements from the breathing zone of Welsh coal miners was characterised by a log-normal distribution. This observation has been confirmed by other researchers as described by Rappaport (1991) in an excellent review of the topic.

Since the publication in 1977 of the NIOSH Sampling Strategy Manual, considerable effort has been expended in better defining the bounds of occupational exposure assessment. In this regard the British Occupational Hygiene Society through its publications (BOHS 1989, 1993), and the American Industrial Hygiene Association through the publications of its Exposure Assessment Strategies Committee (AIHA 1991, 1998), have been leaders. More recently the Australian Institute of Occupational Hygienists has published a similar guideline (Grantham 2001).

In the past decade numerous researchers have explored ways of improving the understanding of occupational hygienists of exposure assessment. The classic papers of Rappaport (1991) and Kromhout et al (1993) have been key drivers in this endeavour and have no doubt led to the current level of understanding of this complex topic.

7.4.2 Selection of an Exposure Standard

Grantham (2001) describes monitoring as the process of conducting a measurement or series of measurements of the concentrations of airborne contaminants that workers are exposed to during the course of a normal working day.

It is possible to make a useful risk assessment of worker exposure only if two key components are available. These are:

i) A reliable estimate of exposure
ii) A standard for means of comparison

The second of these components (Workplace Exposure standards) is available for many contaminants, but not all. Unfortunately, diesel particulate falls into the category of no universally recognised exposure standard.

In terms of the mining industry only four countries (Germany, Canada, USA and Australia) have either attempted to promulgate or have promulgated exposure standards. A short summary of the varying approach of these countries gives some insight into the problem with selecting an appropriate standard for use in an exposure assessment model.

7.4.2.1 *Germany*

Germany has adopted a pragmatic approach to the use of a diesel particulate exposure standard within the mining industry. Dahman (2003) indicates that for underground non-coal mines and construction activities a value of 0.3 mg/m^3 elemental carbon is used under the “Technical Rules for Toxic Substances” system.

Due to the potential for interference from coal dust, the approach in coal mines is practically orientated. In this situation operators calculate the potential exposure from vehicle emission rates and ventilation airflow in every production area. If the calculated exposure is above 0.3 mg/m^3 elemental carbon, either the ventilation is increased or the amount of diesel machinery is reduced.

No information was available as to how vehicle emission rates are calculated or measured. This is a significant issue as modifications to underground mining equipment may influence the generation of emissions. Similarly, the level of maintenance would also be a factor on engine particulate emissions.

7.4.2.2 ***Canada***

Canada presents a similar situation to Australia with state governments promulgating exposure standards, thus giving rise to variations. Grenier (2003) indicates that the majority of the provinces use 1.5 mg/m^3 respirable combustible dust (RCD) as their exposure standard. Two provinces (Quebec and Ontario) are investigating an alternative value; a figure of 0.6 mg/m^3 RCD being the most likely.

7.4.2.3 ***United States of America (USA)***

In the USA the Mine Safety and Health Administration (MSHA) has adopted different approaches for the metal/non-metal and coal mining sectors. In the metal/non-metal sector an exposure limit of 0.16 mg/m^3 (measured as total carbon) was promulgated in 2001 (MSHA 2001).

This standard was challenged in the courts and a settlement (MSHA 2002) reached where no citations would be issued for exposures over a 0.4 mg/m^3 interim limit in the period 20 July 2002 to 19 July 2003. In this period MSHA and operators would partner to seek practical solutions to the many problems that exist.

In regard to coal mines, MSHA adopted a raw exhaust standard of 2.5 g/hr diesel particulate (MSHA 2001). Little or no information exists as to the derivation of this value and its link to atmospheric exposures remains unclear.

The other organisation in the USA that has proposed an exposure standard that has been linked to mining operations is the American Conference of Governmental Industrial Hygienists (ACGIH). The history of their proposal spans the period 1995 – 2003 and is documented in Table 7.3.

Table 7.3
History of ACGIH Diesel Particulate Standard

Year	Proposed Standard
1995	0.15 mg/m^3, A2 (suspected human carcinogen)
1999	0.05 mg/m^3, A2 (suspected human carcinogen)
2001	0.02 mg/m^3, A2 (suspected human carcinogen) and measured as elemental carbon
2003	Withdrawn

7.4.2.4 *Australia*

Within Australia the only current reference to an exposure standard for diesel particulate is in the publication "Diesel Emissions in Underground Mines – Management and Control" produced by the NSW Minerals Council (1999). The document states:

"Determining safe exposure levels for diesel particulate (DP) is more complex (than gaseous emissions) due to evolving scientific knowledge about the health effects of DP and difficulty in accurately measuring DP levels in occupational environments, particularly underground coal mines.

A number of recognised overseas authorities have published or are proposing exposure standards for DP measured in terms of total carbon or elemental carbon. The USA Mine Safety and Health Administration has proposed a workplace exposure standard of 0.16 mg/m^3 total carbon in metal and non-metal mines, which equates to about 0.2 mg/m^3 DP.

Research measuring personal exposure to DP of over 1,000 employees in NSW, WA and Queensland coal and metalliferous mines has found that at levels of 0.2 mg/m^3 or below, the effects of irritation from DP are minimal. However, due to lack of valid long term studies it is not possible to state whether long term exposure to this 0.2 mg/m^3 DP level would prevent the development of diseases such as cancer."

7.4.2.5 ***Summary***

Given the wide divergence of proposals on an appropriate exposure standard and the link between the NSW Minerals Council value of 0.2 mg/m^3 (as diesel particulate) to the MSHA value for metal/non-metal mines of 0.16 mg/m^3 (as total carbon) it was considered appropriate to use a value of 0.2 mg/m^3 DP in the exposure assessment model selected.

This approach had the added advantage in that all data collected by the Tower Colliery Diesel Research Group was via gravimetric methods and thus measured as diesel particulate.

7.4.3 Overview of Data Treatment

As Grantham (2001) describes, a reliable estimate of exposure is difficult to obtain as the level of contaminants in the atmosphere that a worker may be exposed to can be influenced significantly by environmental factors, work practices, the method used to make the measurement, the method used to evaluate the data and the variability of the concentration of the contaminant in the atmosphere relative to the position of the person being monitored.

Any assessment (employee exposure or control technology effectiveness) based on a single sample for a single day will have errors of space (location) and time and will have little to link this result to the real workplace exposure situation. By accounting for as many influencing factors as is practicable it is possible to ensure a greater level of confidence in the measurement of workplace exposures.

The use of statistical sampling and assessment procedures (NIOSH 1977) has assisted in solving the problem of how to correctly (or more accurately) measure workplace exposures.

While statistically based sampling and evaluation of workplace exposures is very useful in giving a more accurate picture of employee exposures, it is not wise to consider it as being the absolute test. There are many assumptions (and thus potential errors) in such programmes but by controlling as many influencing factors as is practicable a better estimate of exposure will be guaranteed.

When the Tower Colliery Research Group undertook the measurements of employee exposure to diesel particulate no statistical exposure assessment of the data took place due to the key researcher leaving the employment of BHP Pty Ltd.

Consequently, it was felt that such a treatment of the data set would be useful and after reviewing a number of approaches it was considered appropriate to follow a similar strategy to that proposed by the American Industrial Hygiene Exposure Assessment Strategies Committee (AIHA 1998).

The key elements of the adopted strategy were:

- Using the worksheets used by the Tower Colliery Research Group a number of Homogeneous Exposure Groups (HEGs) were assigned on the basis of classification and location (eg driver – longwall). Further HEGs were classified on the basis of mine, location and classification (eg Appin – longwall – driver). Further sub groups of HEGs were identified on the basis of job type (eg chock transportation) and mine, equipment and job type (eg Appin – chock transporter – moving supports).

- As no control could be exercised over the number of samples collected, it was considered appropriate to limit HEG definitions to a minimum of six samples. This was based on the AIHA Exposure Assessment Strategies Committee (AIHA 1991) advice that below six samples too much uncertainty exists with each parameter (and hence the exposure distribution).

- Given that it is generally accepted that occupational hygiene data follows a lognormal distribution in most cases (Oldham 1953, NIOSH 1997, Rappaport 1991, BOHS 1989, BOHS 1993, AIHA 1991, AIHA 1998), all data was tested for log-normality.

Data that indicated a probable lognormal distribution was included for further analysis, while data showing a normal distribution was deleted from further analysis on the basis that it probably did not represent a true HEG.

Four techniques were used to test log-normality. These were:

- *Shapiro-Wilk W-Test*

  As discussed in Section 4.7.1 the Shapiro Wilk W-Test is a means by which the degree of conformity or "goodness of fit" of a data set to a distribution can be assessed. The Shapiro Wilk W-Test is considered one of the most powerful "goodness of fit" tests for normal or lognormal data when n is fairly small (AIHA 1998).

- *Skewness*

  The skewness statistic is a measure of the central tendency of a distribution, and thus the skewness values of the normal distribution and the lognormal distribution can be compared to assist in a determination of which distribution is a better fit for the dataset.

  To use the skewness for goodness of fit it is necessary to calculate the skewness for both normal and lognormal distributions. The one that is closer to zero is the better fit (according to this statistic).

- *Straight Line Probability Plot*

  The plotting of data on probability paper can provide a visual assessment as to whether a dataset is following a normal or lognormal distribution depending on the paper used.

Both normal and lognormal probability paper have a probability scale on one axis with the median (50^{th} percentile) at the midpoint and percentage units that widen as they move away from the 50% point in both directions. The other axis is either log (lognormal) or linear (normal) for plotting the concentration data.

- *Cumulative Distribution Function Plot (CDF)*

  The cumulative distribution function, commonly referred to as the CDF, is the parametric curve against which the rank probability of a dataset can be compared. The formula for calculating the CDF is:

$$\text{CDF} = \int \frac{1}{s\sqrt{2\pi}} \cdot e^{-1/2\left(\frac{x_i - M}{s}\right)^2}$$

Where χ_1 stands for the data points
M stands for the mean
S stands for the standard deviation

CDF plots are generally such that they provide a good visual assessment as to whether a dataset follows either a normal or lognormal distribution.

While the Shapiro Wilk W-Test provides the best measure of "goodness of fit", the other techniques provide confirmatory evidence.

- As diesel particulate is considered to be a chronic acting substance, the use of the average exposure of a HEG is considered a useful parameter for evaluating the potential health risk (AIHA 1998).

Given the variability of occupational hygiene data the use of the Minimum Variance Unbiased Estimate (MVUE) is a better descriptor of average exposure (AIHA 1998, BOHS 1989) than the geometric means. As the MVUE will rarely ever equal the data sets true value the upper and lower confidence limits (UCL, LCL) were also calculated using Land's "exact" procedure. Land's procedure is considered appropriate as it calculates exact confidence limits for the true arithmetic mean of a lognormal distribution.

Land's exact confidence limits for the arithmetic mean of a dataset is calculated from the following formula (Land 1993).

$$CL = \exp\left[\ln(\hat{u}) + C\frac{S_y}{\sqrt{n-1}}\right]$$

	$\overline{y}$	=	Mean of the dataset
Where	Sy	=	Standard deviation of the log transformed data where $y = \ln(\chi)$
	C	=	Land's C-factor derived from Land's tables (Land 1993)
	n	=	Number of data samples
	$\hat{u}$	=	$\exp(\overline{y} + ½ S_y^2)$

Using the MVUE as the decision option in terms of exposure the following criteria were adopted.

1. If the 95% UCL of the MVUE was less than 0.2 mg/m^3 (exposure standard) – workplace exposures were acceptable.

2. If the MVUE was less than 0.2 mg/m^3, which in turn was less than the MVUE UCL – professional judgement was exercised based on personal experience.

3. If the MVUE was greater than or equal to 0.2 mg/m^3 – workplace exposures were unacceptable.

- In order to compare the various HEGs for similarity, further analysis was undertaken using the principles of analysis of variance (ANOVA).

  The selection of data for ANOVA is critical and it is appropriate that at least three results be available, collected over at least three workdays in a random manner. In all cases these parameters appeared to be achieved, however the lack of good identification records in regard to specific diesel equipment limited the available data.

  ANOVA was also used to evaluate the effectiveness of the various control technologies tested by the Tower Colliery Diesel Research Group.

7.5 WORKPLACE EXPOSURE DATA

7.5.1 Assignment of Homogeneous Exposure Groups

In the first instance broad HEGs were assigned on the basis of groupings used by the Tower Colliery Research Group. These were essentially based on the experience of mine personnel as to the level of association with diesel vehicle activity. This resulted in the HEGs listed in Table 7.4.

Table 7.4
Initial HEG Structure for Tower Colliery Exposure Data

HEG	Description	Number of Mines	Number of Samples
1	Longwall – Driver	3	62
2	General Underground – Driver	6	79
3	Transport Roads – Driver	6	92
4	General Underground – General Hand	1	18
5	Longwall – General Hand	1	29
6	Panel – General Hand	1	34
7	Transport Roads – General Hand	1	13

As can be observed, numerous samples covering multiple mines is available for HEGs 1, 2 and 3 but data for all other HEGs is restricted to one mine (Tower Colliery).

Examination of these HEGs for lognormality resulted in the following observations (Table 7.5).

Table 7.5
Lognormality Tests for Initial HEG Data

HEG	"W" Test	Skewness	Probability Plot	CDF Plot
1	Lognormal	Lognormal	Lognormal	Lognormal
2	Both Distributions Rejected	Lognormal	Lognormal	Lognormal
3	Lognormal	Lognormal	Lognormal	Lognormal
4	Lognormal	Lognormal	Lognormal	Lognormal
5	Lognormal	Lognormal	Lognormal	Lognormal
6	Neither Distribution Rejected	Normal	Inconclusive	Inconclusive
7	Neither Distribution Rejected	Lognormal	Lognormal	Lognormal

Examples of probability and CDF plots are provided for HEG 1 in Figures 7.2 – 7.5.

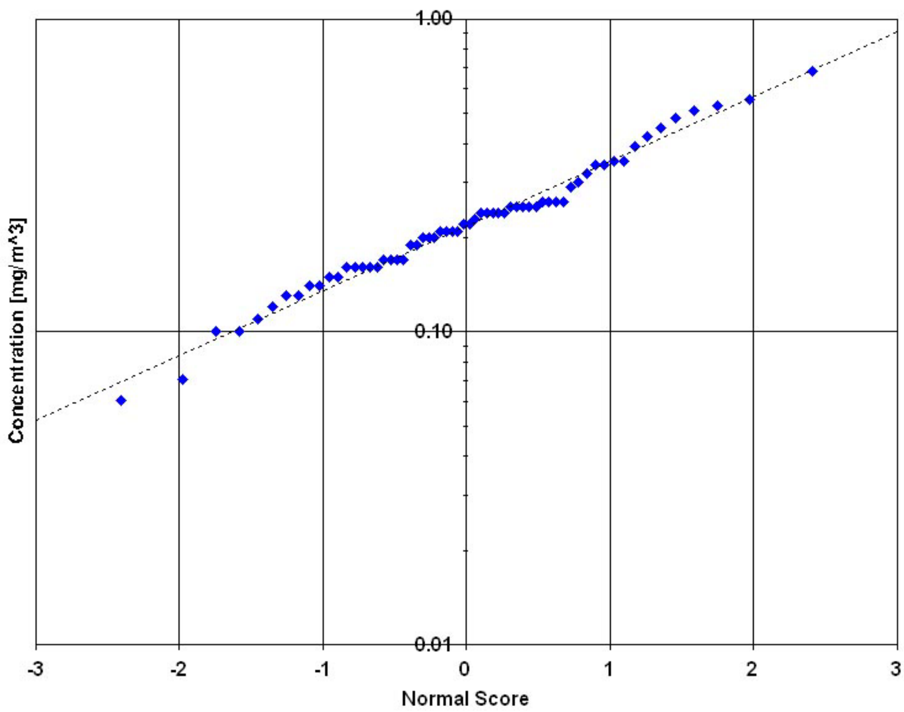


Figure 7.2
Probability Plot for HEG 1 (Lognormal)

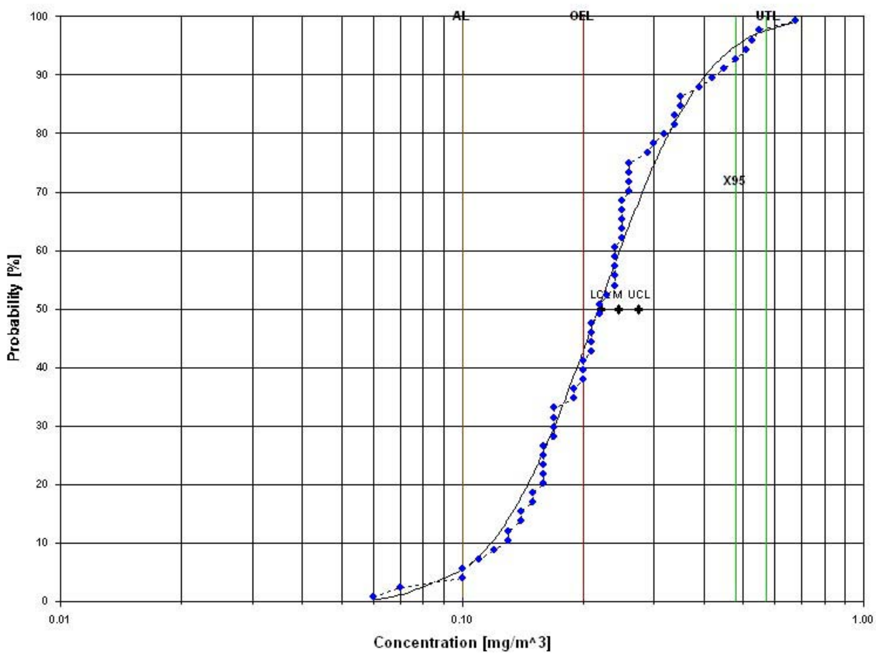


Figure 7.3
Cumulative Distribution Function Plot for HEG 1 (Lognormal)

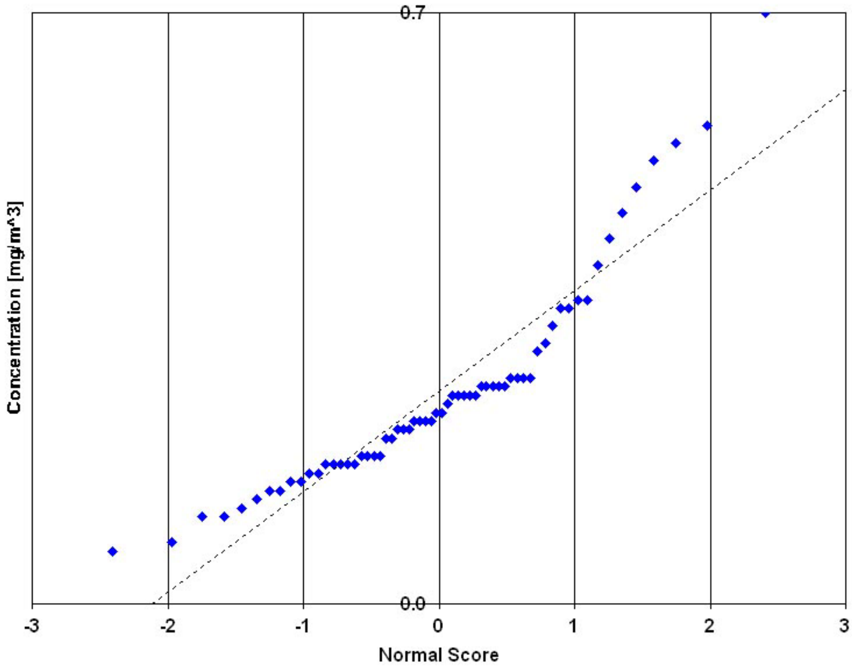


Figure 7.4
Probability Plot for HEG 1 (Normal)

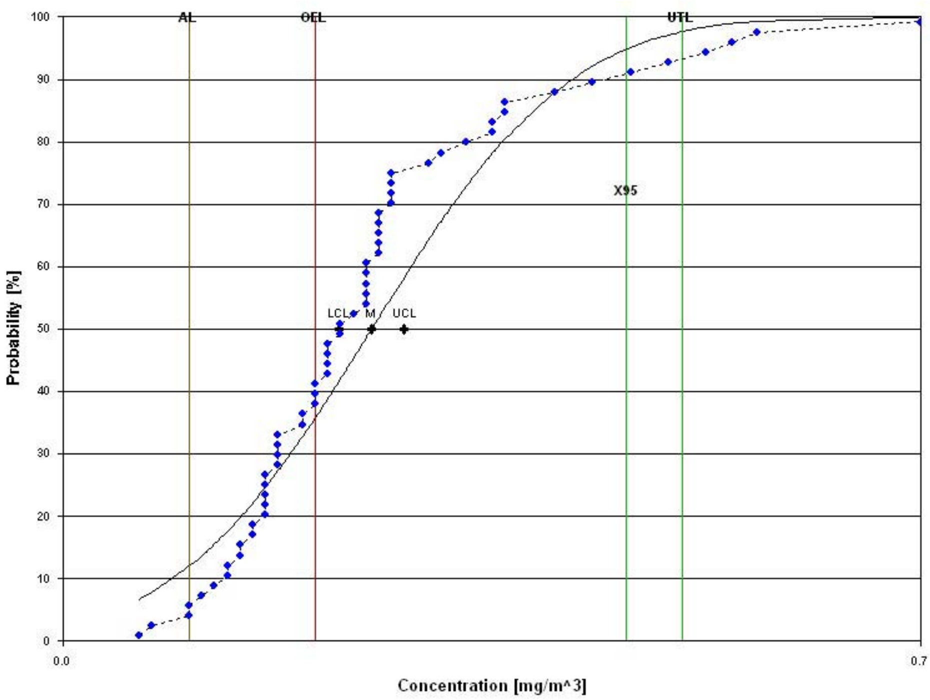


Figure 7.5
Cumulative Distribution Function Plot for HEG 1 (Normal)

The data in Figure 7.2 can be seen to be well distributed and the CDF plot (Figure 7.3) follows the CDF curve closely.

If reference is made to Figures 7.4 and 7.5, the data does not plot on a straight line nor does the data in Figure 7.5 follow the CDF curve.

From these observations it is clear that this dataset more closely follows a lognormal distribution. This approach, along with the Shapiro-Wilk W-Test and the skewness comparison, was used to establish if the various HEGs followed a lognormal distribution.

Based on the results recorded in Table 7.5 HEG 6 (Panel – General Hand) data was removed from further analysis.

The second classification of data into HEGs was based on the location and activity at individual mines. This resulted in the HEGs listed in Table 7.6. Only HEGs with more than six (6) data points have been included.

Table 7.6
HEG Structure Based on Mine – Location - Activity

Mine	HEG	Description	Number of Samples
Appin	A1	Longwall – Driver	11
Appin	A2	General Underground – Driver	6
Baal Bone	B1	General Underground – Driver	13
Crinum	C1	Longwall – Driver	11
Gretley	G1	Transport Roads – Driver	8
South Bulli	S1	Transport Roads – Driver	13
Tower	T1	General Underground – General Hand	18
Tower	T2	Longwall – General Hand	29
Tower	T3	Transport Roads – General Hand	13
Tower	T4	Longwall – Driver	40
Tower	T5	General Underground – Driver	38
Tower	T6	Transport Roads – Driver	27

Mine	HEG	Description	Number of Samples
Ulan	U1	General Underground – Driver	6
Ulan	U2	Transport Roads – Driver	10
West Cliff	W1	General Underground – Driver	8
West Cliff	W2	Transport Roads – Driver	16
West Wallsend	WW1	General Underground – Driver	8
West Wallsend	WW2	Transport Roads – Driver	7

Examination of these HEGs for lognormality resulted in the following observations (Table 7.7).

Table 7.7
Lognormality Tests for Mine – Location – Activity HEGs

HEG	"W" Test	Skewness	Probability Plot	CDF Plot
A1	Lognormal	Lognormal	Lognormal	Lognormal
A2	Normal	Normal	Inconclusive	Inconclusive
B1	Normal	Normal	Inconclusive	Inconclusive
C1	Normal	Normal	Inconclusive	Normal
G1	Lognormal	Lognormal	Lognormal	Lognormal
S1	Lognormal	Lognormal	Lognormal	Lognormal
T1	Lognormal	Lognormal	Lognormal	Lognormal
T2	Lognormal	Lognormal	Lognormal	Lognormal
T3	Lognormal	Lognormal	Lognormal	Lognormal
T4	Lognormal	Lognormal	Lognormal	Lognormal
T5	Lognormal	Lognormal	Lognormal	Lognormal
T6	Lognormal	Lognormal	Lognormal	Lognormal
U1	Lognormal	Lognormal	Lognormal	Lognormal
U2	Lognormal	Lognormal	Inconclusive	Inconclusive
W1	Normal	Normal	Inconclusive	Inconclusive
W2	Both Distributions Rejected	Normal	Inconclusive	Inconclusive
WW1	Normal	Normal	Inconclusive	Inconclusive
WW2	Lognormal	Lognormal	Lognormal	Lognormal

Based on these results, the following HEGs were removed from further analysis:

- Appin – General Underground Driver (A2)
- Baal Bone – General Underground Driver (B1)
- Crinum – Longwall Driver (C1)
- West Cliff – General Underground Driver (W1)
- West Cliff – Transportation Roads Driver (W2)
- West Wallsend – General Underground Driver (WW1)

The third classification of data into HEGs was based on job type at all mines. This resulted in the HEGs listed in Table 7.8. Again, only HEGs with more than six data points have been included.

Table 7.8
HEG Structure Based on Job Type at All Mines

HEG	Description	Number of Samples
CT	Chock Transportation	36
ILW	Installing Longwall Face	41
RLW	Retrieval of Longwall Face	8
P	Panel Duties	25
BI	Belt Installation	13
TM	Tramming Miner	7
GR	Grading Roads	22
SD	Supply Delivery	57
TX	Taxi	25

Examination of these HEGs for lognormality resulted in the following observations (Table 7.9).

Table 7.9
Lognormality Tests for Job Type at All Mine HEGs

HEG	"W" Test	Skewness	Probability Plot	CDF Plot
CT	Lognormal	Lognormal	Lognormal	Lognormal
ILW	Lognormal	Lognormal	Lognormal	Lognormal
RLW	Lognormal	Lognormal	Lognormal	Lognormal
P	Lognormal	Lognormal	Lognormal	Lognormal
BI	Lognormal	Lognormal	Lognormal	Lognormal
TM	Lognormal	Lognormal	Lognormal	Lognormal
GR	Lognormal	Lognormal	Lognormal	Lognormal
SD	Lognormal	Lognormal	Lognormal	Lognormal
TX	Lognormal	Lognormal	Lognormal	Lognormal

The final classification of data into HEGs is based on equipment and job type at individual mines. This resulted in the HEGs listed in Table 7.10.

Table 7.10
HEG Structure Based on Individual Mines – Equipment Type and Job Type

Mine	HEG	Equipment	Job Type	No. of Samples
Appin	A – CT	Chock Transporter	Moving Roof Supports	6
Appin	A – DMC	Diesel Man Car	Personnel Transportation	6
Baal Bone	B – Ei	Eimco 913	General Underground	9
Crinum	C – Ei	Eimco EJ130	General Underground	7
Gretley	G – MPV	Multi Purpose Vehicle	Transportation Roads – Driver	6
South Bulli	S – Lo	Diesel Loco	Transportation Roads – Driver	13
Tower	T – Ei(1)	Eimco 913	General Underground	8
Tower	T – Ei(2)	Eimco 913	Longwall Duties	11
Tower	T – Ei(3)	Eimco 913	Panel Duties	7
Tower	T – Ei(4)	Eimco 913	Transportation Roads – Driver	7
Tower	T – B	Bagshaw	General Duties	9
Tower	T – CT	Chock Transporter	Moving Roof Supports	24

Mine	HEG	Equipment	Job Type	No. of Samples
Tower	T – D(1)	Domino Minesmobile	General Underground	6
Tower	T – D(2)	Domino Minesmobile	Panel Duties	8
Tower	T – MPV(1)	Multi Purpose Vehicle	General Underground	17
Tower	T – MPV(2)	Multi Purpose Vehicle	Transportation Roads – Driver	16
Tower	T – PJB	PJB Personnel Transporter	Personnel Movement	10
Tower	T – W	Wagner	General Duties	6
West Cliff	W – D(1)	Domino Minesmobile	General Underground	6
West Cliff	W – D(2)	Domino Minesmobile	Transportation Roads – Driver	7
West Cliff	W – G	Grader	Transportation Roads – Driver	6

Examination of these HEGs for lognormality resulted in the following observations (Table 7.11).

Table 7.11
Lognormality Tests for Individual Mines, Equipment Type and Job Type

HEG	"W" Test	Skewness	Probability Plot	CDF Plot
A – CT	Lognormal	Lognormal	Lognormal	Lognormal
A – DMC	Normal	Normal	Inconclusive	Inconclusive
B – Ei	Normal	Normal	Inconclusive	Normal
C – Ei	Lognormal	Lognormal	Inconclusive	Inconclusive
G – MPV	Lognormal	Lognormal	Lognormal	Lognormal
S – LO	Lognormal	Lognormal	Lognormal	Lognormal
T – Ei(1)	Lognormal	Lognormal	Lognormal	Lognormal
T – Ei(2)	Lognormal	Lognormal	Lognormal	Lognormal
T – Ei(3)	Normal	Normal	Normal	Normal
T – Ei(4)	Both Distributions Rejected	Lognormal	Lognormal	Inconclusive
T – B	Lognormal	Lognormal	Lognormal	Lognormal
T – CT	Lognormal	Lognormal	Lognormal	Lognormal
T – D(1)	Lognormal	Lognormal	Lognormal	Lognormal

HEG	"W" Test	Skewness	Probability Plot	CDF Plot
T – D(2)	Lognormal	Lognormal	Lognormal	Lognormal
T – MPV(1)	Lognormal	Lognormal	Lognormal	Lognormal
T – MPV(2)	Normal	Normal	Inconclusive	Normal
T – PJB	Lognormal	Lognormal	Lognormal	Lognormal
T – W	Normal	Normal	Inconclusive	Inconclusive
W – D(1)	Lognormal	Lognormal	Lognormal	Lognormal
W – D(2)	Lognormal	Lognormal	Inconclusive	Lognormal
W – G	Lognormal	Lognormal	Lognormal	Lognormal

Based on the above lognormality tests, data from the following HEGs was removed from further analysis:

- Appin – Diesel Man Cars
- Baal Bone – Eimco 913 General Underground
- Tower – Eimco 913 Panel Duties
- Tower – MPV Transportation Roads (Driver)
- Tower – Wagner General Duties

In summary, of the 55 possible HEGs assigned, 12 were rejected due to lack of lognormality of the exposure data.

7.5.2 Exposure Assessment Results

All HEGs considered to follow a lognormal distribution were further analysed using the techniques described in Section 7.4.3 with the following outcomes.

Table 7.12
Initial HEGs Exposure Assessment

HEG	Description	GM (mg/m^3)	GSD	MVUE (mg/m^3)	LCL & UCL (mg/m^3)
1	Longwall – Driver	0.22	1.61	0.25	0.22 – 0.28
2	General Underground – Driver	0.14	1.82	0.17	0.15 – 0.20

HEG	Description	GM (mg/m³)	GSD	MVUE (mg/m³)	LCL & UCL (mg/m³)
3	Transport Roads – Driver	0.17	1.76	0.20	0.18 – 0.23
4	General Underground – General Hand	0.12	1.73	0.14	0.12 – 0.19
5	Longwall – General Hand	0.19	1.56	0.21	0.18 – 0.25
6	Transport Roads – General Hand	0.15	1.63	0.16	0.13 – 0.22

Using the decision criteria listed in Section 7.4.3 all HEGs except No. 4 (General Underground – General Hand) would be considered to be in non-compliance with the exposure standard of 0.2 mg/m^3 as the Land's (1993) 95% UCL exceeds the exposure standard.

This outcome suggests a level of similarity between exposures of personnel working in high production areas (longwall) of mines with resultant diesel activity and areas where diesel activity is lower (transport roads). To test this suggestion ANOVA comparisons were carried out on the initial HEGs (Table 7.13). The null hypothesis (H_0) tested was that there is no significant difference between the exposures of workers to diesel particulate within the indicated HEGs. The alternate hypothesis (H_A) is that there is a significant difference between the exposures of workers to diesel particulate within the indicated HEGs.

One interesting outcome from the results listed in Table 7.12 is the non-compliance of exposures in transportation roads. These had traditionally thought to be acceptable due to the high air volumes, however numerous diesel vehicle movements may result in increased diesel particulate levels.

Table 7.13
ANOVA of Initial HEGs

Description	Null Hypothesis	F Test Statistic	F Critical Value $\alpha_{0.05}$
Driver – Longwall/GU/Transport Roads (HEG 1, 2, 3)	Rejected	10.06	3.0
Driver – GU/Transport Roads (HEG 2, 3)	Rejected	4.222	3.84
Driver – Longwall/Transport Roads (HEG 1, 3)	Rejected	7.519	3.84
Driver – Longwall/GU (HEG 1, 2)	Rejected	20.6	3.84
Longwall – Driver/General Hand (HEG 1, 5)	Not Rejected	1.702	3.96
General Hand – Longwall/Transport Roads/GU (HEG 4, 5, 7)	Rejected	5.819	2.72
General Hand – Transport Roads/GU (HEG 4, 7)	Not Rejected	1.67	4.04

From the above analysis only HEGs 1 and 5 (Longwall – Driver/ General Hand) and HEGs 4 and 7 are statistically equivalent. This is consistent with known diesel activity in both areas and is within expectations.

Table 7.14
Exposure Assessment for Individual Mines – Location and Activity

Mine	HEG	Description	GM (mg/m³)	GSD	MVUE (mg/m³)	LCL & UCL (mg/m³)
Appin	A1	Longwall – Driver	0.22	1.84	0.26	0.19 – 0.41
Gretley	G1	Transport Roads – Driver	0.18	1.19	0.18	0.16 – 0.21
South Bulli	S1	Transport Roads – Driver	0.14	1.55	0.15	0.13 – 0.20
Tower	T1	General Underground – General Hand	0.12	1.73	0.14	0.12 – 0.19
Tower	T2	Longwall – General Hand	0.19	1.56	0.21	0.18 – 0.25
Tower	T3	Transport Roads – General Hand	0.15	1.63	0.16	0.12 – 0.22
Tower	T4	Longwall – Driver	0.21	1.61	0.24	0.21 – 0.28

Mine	HEG	Description	GM (mg/m³)	GSD	MVUE (mg/m³)	LCL & UCL (mg/m³)
Tower	T5	General Underground – Driver	0.16	1.63	0.18	0.16 – 0.21
Tower	T6	Transport Roads – Driver	0.22	1.61	0.25	0.22 – 0.30
Ulan	U1	General Underground – Driver	0.21	1.38	0.22	0.18 – 0.31
Ulan	U2	Transport Roads – Driver	0.21	1.28	0.21	0.19 – 0.25
West Wallsend	WW2	Transport Roads – Driver	0.20	1.91	0.23	0.16 – 0.50

The above data indicates that the Land's 95% UCL for exposures for all HEGs except T1 (Tower Colliery – General Underground / General Hand) exceeds the exposure standard under the assessment criteria being used thus indicating that workers in all HEGs except T1 are potentially over-exposed to diesel particulate.

As with the initial HEG data the exposures for transportation roads are higher than expected given the high ventilation volumes in these areas.

ANOVA of usable data for the exposures detailed in Table 7.14 is provided in Table 7.15. The null hypothesis (H_0) tested is that there is no significant difference in worker exposure to diesel particulate for drivers in longwall panels at Appin and Tower Colliery and also for drivers in transportation roads at Ulan, West Wallsend and Tower Collieries. The alternate hypothesis (H_A) is that there is a significant difference in worker exposure to diesel particulate for drivers in longwall panels at Appin and Tower Colliery and also for drivers in transportation roads at Ulan, West Wallsend and Tower Collieries.

Table 7.15
ANOVA For Individual Mines – Location and Activity

Description	Null Hypothesis	F Test Statistic	F Critical Value $\alpha_{0.05}$
Longwall (Driver) Appin/Tower (HEGs A1, T4)	Not Rejected	0.0222	4.04
Transportation Roads (Driver) – Ulan/ West Wallsend/Tower (HEGs U2, WW2, T6)	Not Rejected	0.2696	3.18

These comparisons are within expectations and clearly demonstrate compatibility of exposures at different mines when performing the same activity in similar locations. This is important as it suggests that the vehicle itself may be the dominant factor in exposure determination as no two mines have comparative conditions.

Table 7.16
Exposure Assessment For Job Type at All Mines

HEG	Description	GM (mg/m^3)	GSD	MVUE (mg/m^3)	LCL & UCL (mg/m^3)
Ct	Chock Transportation	0.26	1.58	0.29	0.25 – 0.33
ILW	Installing Longwall Face	0.21	1.53	0.23	0.20 – 0.26
RLW	Retrieval of LW Face	0.18	1.22	0.18	0.16 – 0.21
P	Panel Duties	0.14	1.66	0.16	0.13 – 0.20
BI	Belt Installation	0.15	1.37	0.15	0.13 – 0.18
TM	Tramming Miner	0.27	1.45	0.28	0.22 – 0.40
GR	Grading Roads	0.15	1.73	0.17	0.14 – 0.22
SD	Supply Delivery	0.15	1.69	0.17	0.15 – 0.20
TX	Taxi	0.10	2.02	0.13	0.10 – 0.17

The above data indicates that the Land's 95% UCL for exposures for all HEGs (job types), except belt installation (BI) and taxi driver (TX), at all mines either equal or exceed the exposure standard under the assessment criteria being used and thus workers in these HEGs are potentially over-exposed to diesel particulate.

ANOVA of usable data for the exposures detailed in Table 7.16 are provided in Table 7.17. The null hypothesis (H_0) tested is that there is no significant difference in worker exposure to diesel particulate for operators working in the same area of mines but performing different tasks. The alternative hypothesis (H_A) is that there is a significant difference in worker exposure to diesel particulate for operators working in the same area of mines but performing different tasks.

Table 7.17
ANOVA of Job Type at All Mines

Job Type	Null Hypothesis	F Test Statistic	F Critical Value $\alpha_{0.05}$
Check Transportation/Installing LW Face/Retrieving LW Face (HEGs CT, ILW, RLW)	Rejected	3.952	3.11
Installing LW Face/Retrieving LW Face (HEGs ILW, RLW)	Not Rejected	1.22	4.04
Grading Roads/Supply Delivery/Taxi (HEGs GR, SD, TX)	Rejected	4.751	3.11
Grading Roads/Supply Delivery (HEGs GR, SD)	Not Rejected	0.03592	3.96

These results are again within expectations. Installation and retrieval of the longwall face is essentially the same process (except in reverse for retrieval) and the transportation of chocks is usually in main roadways, thus giving rise to different exposure profiles.

Similarly, grading roads and supply delivery would be expected to be similar, with the taxi driver being lower probably due to the smaller capacity engine used in transportation vehicles.

It is again interesting to note that specific jobs at all mines (installing and retrieval of longwall faces, grading roads and supply delivery) appear to have similar exposure profiles. Given the numerous variants at individual mines this suggests the vehicle output overrides all other factors.

The final exposure data for individual mines and equipment job type is provided in Table 7.18.

Table 7.18
Exposure Assessment For Individual Mines, Equipment and Job Type

HEG	Mine	Equipment	Job Type	GM (mg/m^3)	GSD	MVUE (mg/m^3)	LCL & UCL (mg/m^3)
A - CT	Appin	Chock Transporter	Moving Supports	0.25	2.29	0.32	0.19 – 1.29
C – Ei	Crinum	Eimco EJ130	General U/G	0.23	1.45	0.24	0.19 – 0.34
G - MPV	Gretley	MPV	Transportation Roads	0.17	1.20	0.18	0.15 – 0.21
S – Lo	South Bulli	Loco	Transportation Roads	0.14	1.55	0.15	0.13 – 0.20
T – Ei(1)	Tower	Eimco 913	General U/G	0.14	1.60	0.15	0.12 – 0.23
T – Ei(2)			Longwall Duties	0.20	1.92	0.25	0.18 – 0.41
T – Ei(4)			Transportation Roads	0.28	1.43	0.29	0.23 – 0.41
T – B		Bagshaw	General Duties	0.21	1.66	0.23	0.18 – 0.35
T – CT		Chock Transporter	Moving Supports	0.23	1.53	0.25	0.22 – 0.30
T – D(1)		Domino	General U/G	0.19	1.37	0.20	0.16 – 0.27
T – D(2)			Panel	0.16	1.62	0.18	0.14 – 0.28
T – MPV(1)		MPV	General U/G	0.17	2.17	0.22	0.17 – 0.36
T – PJB		PJB	Personnel Movement (Transport Roads)	0.16	1.99	0.19	0.14 – 0.35
W – D(1)	West Cliff	Domino	General U/G	0.08	1.74	0.10	0.07 – 0.19
W – D(2)			Transportation Roads	0.08	1.16	0.08	0.08 – 0.09
W – G		Grader	Transportation Roads	0.11	1.37	0.11	0.09 – 0.16

From the above data, the Land's 95% UCL for all HEGs exceeded the exposure standard under the assigned criteria except three from West Cliff, indicating that workers in HEGs at all mines except West Cliff are potentially over-exposed to diesel particulate.

This is an interesting outcome as the Tower Colliery Diesel Research Team (Pratt et al 1995) made the comment that this mine appeared to have consistently lower results to other operations that they had sampled. They suggested a number of factors that may have influenced their results. These were:

- Use of low sulphur fuel
- Good road conditions
- Intensive scheduled maintenance programme
- Restriction of vehicles in ventilation splits (maximum of three vehicles at any one time)
- Computerised weekly exhaust emission testing for gaseous fraction
- Policy of replacement of “older” design engines

ANOVA of usable data from this final HEG grouping is provided in Table 7.19. The null hypothesis (H_0) tested is that there is no significant difference in worker exposure to diesel particulate for the same type of diesel equipment performing the same job at different mines. The alternate hypothesis (H_A) is that there is a significant difference in worker exposure to diesel particulate for the same type of diesel equipment performing the same job at different mines.

Table 7.19
ANOVA For Individual Mines Equipment – Job Type

HEGs	Mines	Equipment	Job Type	Null Hypothesis	F Test Statistic	F Critical Value $\alpha_{0.05}$
A – CT/T – CT	Appin/ Tower	Chock Transporter	Moving Supports	Not Rejected	0.07281	4.2
T – D(1) / W – D(1)	Tower/ West Cliff	Domino Minesmobile	General Underground	Rejected	9.55	4.96

The above results are interesting in that the mean exposures of the HEGs for moving supports with chock transporters at Appin and Tower Collieries are statistically similar. Given the individual differences of the mines, this suggests whatever controls are applied at one mine should work at the other.

The results for Domino Minesmobiles at Tower and West Cliff indicate a statistical difference in the exposure group means. Given these results there is strong evidence that West Cliff Colliery is indeed different in its exposure profile and the comments of Pratt et al (1995) may well be fact.

7.5.3 Equality of Equipment

In order to explore the indications that vehicle diesel particulate generation is the dominant factor in employee exposure profiles, the records of the Tower Colliery Diesel Research Group were further reviewed to obtain multiple vehicles of the same type (which are clearly identified) located at more than one mine. Also the job type needed to be the same or similar to ensure an appropriate comparison was possible.

Unfortunately, very few vehicles were found in the records that were clearly identified. Those that were found are listed in Table 7.20.

Table 7.20
Identifiable Equipment at Individual Mines

Mine	Equipment	Vehicle No.	Job Type	DP mg/m^3
Baal Bone	Eimco 913	405	General Underground	0.27
				0.32
				0.22
				0.27
		406		0.23
				0.20
		407		0.13

Mine	Equipment	Vehicle No.	Job Type	DP mg/m^3
Ulan	Eimco 913	7202	General Underground	0.17
		7207		0.16
				0.15
		7208		0.36
		7213		0.31
Gretley	MPV	1	Transportation Roads	0.18
		2		0.16
				0.23
		4		0.15
		5		0.19
Tower	MPV	93	Transportation Roads	0.31
				0.24
				0.07
		95		0.32
				0.24
		100		0.16
Ulan	Eimco 913	7203	Transportation Roads	0.20
		7208		0.16
		7213		0.26
				0.31
Tower	Eimco 913	5	Transportation Roads	0.25
		6		0.26
		104		0.59
				0.20

ANOVA of the above data resulted in the observations listed in Table 7.21. The null hypothesis (H_0) tested is that there is no significant difference in worker exposure to diesel particulate generated from the same type of diesel equipment performing the same task at different mines. The alternate hypothesis (H_A) is that there is a significant difference in worker exposure to diesel particulate generated from the same type of diesel equipment performing the same task at different mines.

Table 7.21
ANOVA of Identifiable Equipment at Individual Mines

Mines	Equipment	Job Type	Null Hypothesis	F Test Statistic	F Critical Value $\alpha_{0.05}$
Baal Bone – Ulan	Eimco 913	General Underground	Not Rejected	0.2371	4.96
Gretley – Tower	MPV	Transportation Roads	Not Rejected	0.157	5.12
Ulan – Tower	Eimco 913	Transportation Roads	Not Rejected	0.9594	5.99

The above results are a significant outcome in that they indicate that the mean exposures arising from at least three uniquely identifiable units of diesel equipment doing the same job at different mines are statistically equal.

This suggests that any control technology developed for one mine that is focused on the diesel equipment involved will be valid at any other mine provided the job tasks are similar.

7.6 PROPOSED CONTROL TECHNOLOGIES

During the course of its tenure, the Tower Colliery Diesel Research Group evaluated a number of control technologies. All testing was conducted in the Tower Colliery surface test tunnel (Figure 7.1) or the later underground facility.

The technologies or processes investigated included:

- Cleanliness of Intake Air Filters. The Tower Colliery Research Group (Pratt et al 1995) considered that a significant blockage was necessary before any major issue would occur.

- Disposable Exhaust Filters. This was viewed by the Tower Colliery Research Group as a major means by which exhaust diesel particulate levels could be reduced.

- Fuel Quality. Pratt et al (1997) indicates that the research conducted by the Tower Colliery Diesel Research Group suggests that only a marginal reduction in diesel particulate levels arises from low emission fuels over current fuels, however significant reductions in odour do occur. Pratt tested five fuel types, these being:

  1. Low emission aliphatic fuel from Central Queensland (S = 0.01%)

  3. Heating oil based diesel low emission fuel (S = 0.03%)

  7. High sulphur diesel fuel used in Western Australia (S = 0.5%)

  9. Over-the-road diesel fuel from a Sydney refinery (S = 0.16%)

  10. Experimental low emission fuel (S = 0.10%)

- Presence of a water conditioner bath (scrubber tank)

- Cleanliness of vehicle scrubber tanks.

- Chemical decoking of the cylinders and fuel injection system. This was considered to be effective on old engines but probably not sustainable and thus would require frequent treatment.

- Ventilation. Little work was performed in this area due to the complexities of the topic but limited data (Pratt et al 1995) indicated the process of simply doubling ventilation rates for two equal vehicles in a ventilation split may not necessarily result in halving the workplace exposure.

To better understand the effectiveness of these control technologies, ANOVA analysis of available data was undertaken (Table 7.22). The null hypothesis (H_0) tested is that there is no significant difference in atmospheric diesel particulate levels as a result of the various control technology projects investigated by the Tower Colliery Research Group. The alternate hypothesis (H_A) is that there is a significant difference in atmospheric diesel particulate levels as a result of the various control technology projects investigated by the Tower Colliery Research Group.

Table 7.22
ANOVA Comparisons of Control Technologies

Location	Project	Description	Null Hypothesis	F Test Statistic	F Critical Value $\alpha_{0.05}$
Tower Test Tunnel	Intake Air Filters	Comparison of new and used air intake filter on DP concentrations	Not Rejected	2.246	4.96
Tower Test Tunnel	Disposable Exhaust Filters	Comparison of with and without filter on DP concentrations	Rejected	145.3	4.75
Tower Test Tunnel	Fuel Quality Trial	Comparison of all fuels (1, 3, 7, 9, 10)	Rejected	11.27	2.65
		Comparison of fuels 1, 3, 9 & 10	Not Rejected	2.208	2.92
		Comparison of fuels 1 & 3	Not Rejected	3.431	4.6
		Comparison of fuels 1, 3 & 9	Not Rejected	2.167	3.42
		Comparison of fuels 3 & 9	Not Rejected	3.431	4.6
Tower Colliery	In-Mine Fuel Trials (MPV)	Comparison of DP results pre and post use of low emission fuel	Not Rejected	0.8534	4.17
	In-Mine Fuel Trials (PJB)	As above	Not Rejected	4.353	4.54
Tower Test Tunnel	Scrubber Tanks	Comparison of vehicle with and without scrubber tank on DP concentrations	Rejected	14.93	4.96
Tower Test Tunnel	Scrubber Tank Cleanliness	Comparison of DP concentrations pre and post cleaning a scrubber tank	Not Rejected	0.08896	4.96

Location	Project	Description	Null Hypothesis	F Test Statistic	F Critical Value $\alpha_{0.05}$
Tower Test Tunnel	Chemical Decoking	Comparison of exhaust DP levels pre and post decoking after 4 days and after 12 months			
		MPV 93 (4 days)	Not Rejected	3.588	4.75
		MPV 93 (all data)	Not Rejected	3.238	4.41
		MPV 95 (4 days)	Rejected	4.782	4.17
		MPV 95 (all data)	Not Rejected	0.4021	4.125

Examination of the results listed in Table 7.22 is in line with the conclusions of the Tower Colliery Diesel Research Group with the most effective control technology being the DDEF.

Examination of the fuel quality ANOVA data indicates only the inclusion of the high sulphur fuel data (fuel 7) resulted in the mean equality hypothesis being rejected. Thus, the decision by the Tower Colliery Diesel Research Group to introduce low sulphur fuel based on odour reduction rather than diesel particulate reduction (Pratt et al 1997), appears vindicated.

7.7 CONCLUSIONS

The research carried out by the Tower Colliery Diesel Research Group during the period 1990 – 1995 has guided the NSW underground coal mining industry in appropriate measures to control employee exposure to diesel particulate.

By comprehensively reviewing all available data from that period, using exposure assessment techniques and the NSW Minerals Council's exposure standard promulgated in 1999, it is possible to come to the following conclusions:

- Using varying definition criteria, fifty-five (55) possible HEGs were identified. Twelve (12) of these were rejected due to a lack of lognormality of exposure data.

Of the forty-three (43) remaining HEGs a total of thirty-six (36) exceeded the assigned workplace exposure standard of 0.2 mg/m^3 diesel particulate (using the criteria of 95% upper confidence limit for the arithmetic mean estimate (MVUE) exceeding or equal to 0.2 mg/m^3).

- Exposures above the assigned exposure standard were identified in HEGs associated with activity in transportation roads. This is a significant finding as the Tower Colliery Diesel Research Group was of the opinion that high exposures were generally associated with longwall activities and small engines used in transportation vehicles were unlikely to be significant generators of diesel particulate. Davies (2000) identified that personnel transportation vehicles produced more diesel particulate than large units used in longwall moves (comparison was based on equivalent g/kWhr).

  Based on the work of Davies (2000) and employee concerns at one mine, BHP Billiton Illawarra Coal decided to include personnel transportation vehicles in their exhaust filter retrofit programme. The analysis of the Tower Colliery data suggests that this is an appropriate action.

- Analysis of the available exposure data for a number of control technologies clearly highlights disposable exhaust filters as being the most effective.

  The cleanliness of air intake filters and scrubber tanks do not appear to have a significant affect on diesel particulate generation under normal operating conditions. It is clear however that the presence of a water-filled scrubber tank does reduce the concentration of diesel particulate in the vehicle exhaust. This is probably due to physical impaction rather than any other mechanism.

Fuel quality is important and there is a clear relationship between high fuel sulphur levels and diesel particulate. As the concentration of sulphur decreases, the measurable differences become more difficult to separate, however odour levels are significantly reduced.

Chemical decoking of engines does appear effective in the short term but re-treatment at regular intervals would be necessary.

The above outcomes reflect the views expressed by the Tower Colliery Diesel Research Group in 1995. It is clear that disposable exhaust filters will remain the main avenue of emission control for the immediate future.

- While the available data was limited due to vehicles not being clearly identified in the Tower Colliery records, at least three situations at four mines (Table 7.21) indicate there is a relationship between equipment design or type and employee exposure, irrespective of the characteristics of individual mines. This suggests that engine output overloads other factors (eg ventilation differences) in terms of contributing to employee exposures. If this is the case, clearly the focus of future control technologies should be in the area of vehicle exhaust diesel particulate generation. New low emission electronic controlled engines (Section 6) appear to offer some hope in this area.

8. SUMMARY OF CONCLUSIONS

Diesel-powered equipment has been used in Australian underground coal mines since 1941 and is the basis of major productivity advances in recent years.

Since their introduction, colliery employees have expressed concern as to possible adverse health effects arising from exposure to diesel exhaust emissions. The potential for adverse health effects from the gaseous fraction of diesel exhaust have been recognised for many years and controlled through statutory measures.

Since 1988 the focus has centred on the potential for the particulate fraction to give rise to adverse health effects, specifically lung cancer. In the last five years a number of statutory authorities have concluded that diesel particulate is a carcinogen, however the degree of potency is unclear. These findings have been based on large-scale statistical reviews (meta-analysis) of epidemiological studies which are still the subject of debate due to the means by which negative outcomes in epidemiological studies are assessed within the meta-analysis process. It is likely that such debate will continue for some time to come, however sufficient evidence currently exists to suggest worker exposures should be maintained at as low a level as is practical.

Notwithstanding the level of uncertainty regarding the potency of diesel particulate as a carcinogen, there is evidence that exposure to high concentrations gives rise to significant irritant effects. Research within Australia has demonstrated that employees exposed to levels below 0.2 mg/m^3 (as DP) do not exhibit significant irritation effects.

Measures to control the level of diesel particulate in mine atmospheres have been researched for a number of years, however it is only in the past eight years that implementation of basic control technologies have been adopted by some sections of the industry. These technologies are viewed as interim or marginal due to their high operating or implementation cost.

The aim of this research was to explore a number of control technologies to either improve their efficiency or demonstrate their potential for providing significant reductions in employee exposure. The opportunity was also taken to re-examine the original research conducted by the Tower Colliery Research Group to see if the data statistically supported the conclusions which had been made in respect to the various control technologies investigated.

As a result of investigations performed during this research project it is possible to draw the following conclusions.

a) A suitable test procedure has been developed that can quickly be used to evaluate new disposable diesel exhaust filter designs for suitability in respect to filtration efficiency and backpressure.

   Application of this process to filters currently used by BHP Billiton Illawarra Coal has resulted in improvements to filtration efficiency and reduced backpressure. These improvements, coupled together with a change in work practices, have the potential to lower operating costs by approximately $395,000 per annum.

b) Following the incorporation of a Rupprecht & Patashnick Co Inc Series 5100 diesel particulate analyser into a mobile trailer, examination of approximately 68% of the diesel fleet of BHP Billiton Illawarra Coal has highlighted seven out of 66 engines tested as being abnormal.

Investigation as to the reasons for excessive raw exhaust elemental carbon concentrations has highlighted a number of maintenance issues (eg blocked scrubber tanks, incorrectly set tappets, worn injectors).

The process has gained interest from mine site mechanical engineering staff as it has enabled under-powered engines to be returned to improved performance while at the same time controlling emission levels.

Data obtained during the monitoring phase of the project suggests that current statutory ventilation requirements for diesel engines in NSW underground coal mines would be insufficient to control general airbody concentrations to below the best practice standard of 0.2 mg/m^3 DP (0.1 mg/m^3 EC) (NSW Minerals Council 1999). This confirms the importance of controlling diesel particulate at the source (ie engine).

c) A comparison of a 4WD prototype fire-protected vehicle powered with an "over-the-road" diesel engine, to three vehicles currently used within BHP Billiton Illawarra Coal was carried out under mining conditions. The data generated within this project demonstrated that engines of newer design have the potential to reduce atmospheric elemental carbon concentrations by up to 67-90%.

This data is important as it provides added weight to the belief that one practical means of minimising exposure to diesel particulate will be to upgrade to newer technology (eg electronically controlled engines) when either purchasing new or replacing equipment. This process will naturally occur as the most popular engines currently in service within the NSW underground coal industry are no longer available.

Unfortunately, intrinsic safety requirements will delay the introduction of these engines, however industry suppliers are expressing confidence that these hurdles can be overcome.

d) A statistical review of data from the Tower Colliery Diesel Research Group supports the actions taken by the industry as a result of that research.

Two outcomes of the review of substantial significance are:

- At least three situations at four mines indicate there is a relationship between equipment design or type and employee exposure, irrespective of the characteristics of individual mines. This suggests that engine output overloads other factors (eg ventilation differences) in terms of contributing to employee exposures.

  If this is the case, clearly the focus of future control technologies should be in the area of vehicle exhaust diesel particulate generation. New low emission electronically controlled engines appear to offer some hope in this area.

- Exposures above the assigned exposure standard were identified in homogeneous exposure groups associated with activity in transportation roads. This is a significant finding as many researchers limit their monitoring to areas of high activity, eg longwall change-outs. This finding is given added support from the engine monitoring data reported in section 5, where one engine, typically used in transportation vehicles (KIA 6-247), had the highest emission rate.

In summary, it is believed that this project has, through its outcomes, added significant data to the knowledge base and generated positive outcomes for the project supporter, BHP Billiton Illawarra Coal, through improved control technologies at reduced costs. In addition a new diagnostic tool to identify maintenance issues has been successfully trialled and will now become a standard practice within BHP Billiton Illawarra Coal.

Finally, the other beneficiaries from this project are the operators using diesel equipment underground. Actions arising from the research reported in this project have further reduced employee exposure to diesel particulate and thus reduced the potential for adverse health effects.

9. PUBLICATIONS AND PRESENTATIONS

During the course of this project the following presentations were made:

- Diesel Particulate Control Strategies at some Australian Underground Coal Mines; Yant Award Lecture, AIHCE San Diego, USA, June 2002.
- Diesel Particulate – The Australian Experience; Mining Diesel Emissions Conference, Toronto, Canada, October 2002.
- The Efficiency of Diesel Exhaust Filters used in Underground Coal Mines; AIOH Annual Conference, Geelong, December 2002.
- Overseas Update; Coal Services Pty Ltd Diesel Particulate Seminar, Penrith, May 2003.
- Disposable Exhaust Filter Research; Coal Services Pty Ltd Diesel Particulate Seminar, Penrith, May 2003.

As the result of a request from the President of the Australian Institute of Occupational Hygienists (AIOH) a guidance note on diesel particulate (Appendix 3) was prepared in association with Mr Alan Rogers. The majority of the document was prepared using data from this research project. Mr Rogers provided information on atmospheric sampling of diesel particulate (his area of specialist expertise), reviewed the document and made suggestions on improvement. The document was prepared in draft form and made available for two months to the members of the AIOH for review and comment prior to finalisation in February 2004. This document is to be published by the AIOH (www.aioh.org.au).

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APPENDIX 1

TOWER COLLIERY RESEARCH GROUP

EXPOSURE DATA

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Appin	0.21	Bagshaw	Driver	Longwall	21-Nov-1994	ACARP Exposure Data
Appin	0.22	Chock Transporter	Driver	Longwall	19-Nov-1994	ACARP Exposure Data
Appin	0.19	Chock Transporter	Driver	Longwall	20-Nov-1994	ACARP Exposure Data
Appin	0.42	Chock Transporter	Driver	Longwall	21-Nov-1994	ACARP Exposure Data
Appin	0.68	Chock Transporter	Driver	Longwall	21-Nov-1994	ACARP Exposure Data
Appin	0.30	Chock Transporter	Driver	Longwall	22-Nov-1994	ACARP Exposure Data
Appin	0.06	Chock Transporter	Driver	Longwall	23-Nov-1994	ACARP Exposure Data
Appin	0.03	DMC	Driver	General Underground	20-Nov-1994	ACARP Exposure Data
Appin	0.05	DMC	Driver	General Underground	21-Nov-1994	ACARP Exposure Data
Appin	0.04	DMC	Driver	General Underground	22-Nov-1994	ACARP Exposure Data
Appin	0.04	DMC	Driver	Transport Roads	23-Nov-1994	ACARP Exposure Data
Appin	0.05	DMC	Driver	General Underground	24-Nov-1994	ACARP Exposure Data
Appin	0.05	DMC	Driver	General Underground	24-Nov-1994	ACARP Exposure Data
Appin	0.07	Domino	General Hand	Longwall	23-Nov-1994	ACARP Exposure Data
Appin	0.21	DOZER	Driver	Longwall	19-Nov-1994	ACARP Exposure Data
Appin	0.24	DOZER	Driver	Longwall	20-Nov-1994	ACARP Exposure Data
Appin	0.16	DOZER	Driver	Longwall	22-Nov-1994	ACARP Exposure Data
Appin	0.16	DOZER	Driver	Longwall	24-Nov-1994	ACARP Exposure Data
Appin	0.14	Nil Machine	General Hand	Longwall	19-Nov-1994	ACARP Exposure Data
Appin	0.17	Nil Machine	General Hand	Longwall	19-Nov-1994	ACARP Exposure Data
Appin	0.19	Nil Machine	General Hand	General Underground	22-Nov-1994	ACARP Exposure Data
Appin	1.65	Shearer Transporter	Driver	Longwall	20-Nov-1994	ACARP Exposure Data
Baal Bone	0.27	EIMCO 913	Driver	General Underground	28-Nov-1994	ACARP Exposure Data
Baal Bone	0.32	EIMCO 913	Driver	General Underground	28-Nov-1994	ACARP Exposure Data
Baal Bone	0.30	EIMCO 913	Driver	Transport Roads	28-Nov-1994	ACARP Exposure Data

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Baal Bone	0.22	EIMCO 913	Driver	General Underground	29-Nov-1994	ACARP Exposure Data
Baal Bone	0.18	EIMCO 913	Driver	General Underground	29-Nov-1994	ACARP Exposure Data
Baal Bone	0.13	EIMCO 913	Driver	General Underground	29-Nov-1994	ACARP Exposure Data
Baal Bone	0.23	EIMCO 913	Driver	General Underground	30-Nov-1994	ACARP Exposure Data
Baal Bone	0.27	EIMCO 913	Driver	General Underground	30-Nov-1994	ACARP Exposure Data
Baal Bone	0.23	EIMCO 913	Driver	General Underground	30-Nov-1994	ACARP Exposure Data
Baal Bone	0.20	EIMCO 913	Driver	General Underground	30-Nov-1994	ACARP Exposure Data
Baal Bone	0.25	Grader	Driver	Transport Roads	28-Nov-1994	ACARP Exposure Data
Baal Bone	0.17	Grader	Driver	Transport Roads	29-Nov-1994	ACARP Exposure Data
Baal Bone	0.31	Myne Bus	Driver	General Underground	30-Nov-1994	ACARP Exposure Data
Cordeaux	0.09	Loco	Driver	Transport Roads	23-Jul-1997	ACARP Exposure Data
Cordeaux	0.18	Loco	Shunter	Transport Roads	23-Jul-1997	ACARP Exposure Data
Crinum	0.35	DOZER	Driver	Longwall	08-Dec-1997	JCB H&S Trust
Crinum	0.34	DOZER	Driver	Longwall	09-Dec-1997	JCB H&S Trust
Crinum	0.25	DOZER	Driver	Longwall	10-Dec-1997	JCB H&S Trust
Crinum	0.50	Drift Runner	Driver	General Underground	10-Dec-1997	JCB H&S Trust
Crinum	0.13	EIMCO 936	Driver	General Underground	05-Dec-1997	JCB H&S Trust
Crinum	0.25	EIMCO 936	Driver	Longwall	08-Dec-1997	JCB H&S Trust
Crinum	0.29	EIMCO 936	Driver	Longwall	09-Dec-1997	JCB H&S Trust
Crinum	0.13	EIMCO 936	Driver	Longwall	09-Dec-1997	JCB H&S Trust
Crinum	0.22	EIMCO EJ130	Driver	General Underground	05-Dec-1997	JCB H&S Trust
Crinum	0.38	EIMCO EJ130	Driver	Transport Roads	05-Dec-1997	JCB H&S Trust
Crinum	0.17	EIMCO EJ130	Driver	Longwall	08-Dec-1997	JCB H&S Trust
Crinum	0.13	EIMCO EJ130	Driver	Longwall	08-Dec-1997	JCB H&S Trust
Crinum	0.34	EIMCO EJ130	Driver	Longwall	09-Dec-1997	JCB H&S Trust
Crinum	0.24	EIMCO EJ130	Driver	Longwall	10-Dec-1997	JCB H&S Trust

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Crinum	0.22	EIMCO EJ130	Driver	Longwall	10-Dec-1997	JCB H&S Trust
Crinum	0.06	PJB	Driver	General Underground	05-Dec-1997	JCB H&S Trust
Gretley	0.56	EIMCO 912	Driver	General Underground	13-Jul-1994	ACARP Exposure Data
Gretley	0.16	EIMCO 913	Driver	Transport Roads	05-Jul-1994	ACARP Exposure Data
Gretley	0.15	EIMCO 913	Driver	Transport Roads	06-Jul-1994	ACARP Exposure Data
Gretley	0.20	EIMCO 913	Driver	General Underground	07-Jul-1994	ACARP Exposure Data
Gretley	0.23	EIMCO 936	Driver	Transport Roads	13-Jul-1994	ACARP Exposure Data
Gretley	0.19	MPV	Driver	Transport Roads	05-Jul-1994	ACARP Exposure Data
Gretley	0.16	MPV	Driver	Transport Roads	05-Jul-1994	ACARP Exposure Data
Gretley	0.18	MPV	Driver	Transport Roads	07-Jul-1994	ACARP Exposure Data
Gretley	0.23	MPV	Driver	Transport Roads	13-Jul-1994	ACARP Exposure Data
Gretley	0.15	MPV	Driver	Transport Roads	14-Jul-1994	ACARP Exposure Data
Gretley	0.14	MPV	Driver	General Underground	14-Jul-1994	ACARP Exposure Data
South Bulli	0.34	Chock Transporter	Driver	Transport Roads	15-Aug-1994	ACARP Exposure Data
South Bulli	0.47	Chock Transporter	Driver	Transport Roads	15-Aug-1994	ACARP Exposure Data
South Bulli	0.28	Chock Transporter	Driver	Transport Roads	16-Aug-1994	ACARP Exposure Data
South Bulli	0.37	Chock Transporter	Driver	Transport Roads	16-Aug-1994	ACARP Exposure Data
South Bulli	0.10	DMC	Driver	General Underground	03-Aug-1994	ACARP Exposure Data
South Bulli	0.06	DMC	Driver	General Underground	04-Aug-1994	ACARP Exposure Data
South Bulli	0.14	Loco	Driver	Transport Roads	02-Aug-1994	ACARP Exposure Data
South Bulli	0.17	Loco	Shunter	Transport Roads	02-Aug-1994	ACARP Exposure Data
South Bulli	0.14	Loco	Shunter	Transport Roads	03-Aug-1994	ACARP Exposure Data
South Bulli	0.14	Loco	Driver	Transport Roads	03-Aug-1994	ACARP Exposure Data
South Bulli	0.28	Loco	Shunter	Transport Roads	04-Aug-1994	ACARP Exposure Data
South Bulli	0.18	Loco	Driver	Transport Roads	04-Aug-1994	ACARP Exposure Data
South Bulli	0.07	Loco	Shunter	Transport Roads	08-Aug-1994	ACARP Exposure Data

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
South Bulli	0.08	Loco	Driver	Transport Roads	08-Aug-1994	ACARP Exposure Data
South Bulli	0.10	Loco	Shunter	Transport Roads	08-Aug-1994	ACARP Exposure Data
South Bulli	0.28	Loco	Shunter	Transport Roads	09-Aug-1994	ACARP Exposure Data
South Bulli	0.20	Loco	Driver	Transport Roads	09-Aug-1994	ACARP Exposure Data
South Bulli	0.10	Loco	Shunter	Transport Roads	10-Aug-1994	ACARP Exposure Data
South Bulli	0.10	Loco	Driver	Transport Roads	10-Aug-1994	ACARP Exposure Data
South Bulli	0.17	MPV	Driver	General Underground	04-Aug-1994	ACARP Exposure Data
South Bulli	0.18	PET	Driver	General Underground	03-Aug-1994	ACARP Exposure Data
South Bulli	0.19	Wagner	Driver	Longwall	15-Aug-1994	ACARP Exposure Data
South Bulli	0.25	Wagner	Driver	Longwall	16-Aug-1994	ACARP Exposure Data
Tower	0.33	Bagshaw	Driver	Transport Roads	06-Jul-1991	Tower Exposure Data
Tower	0.15	Bagshaw	Driver	General Underground	10-Feb-1992	Tower Exposure Data
Tower	0.19	Bagshaw	Driver	General Underground	11-May-1992	Tower Exposure Data
Tower	0.19	Bagshaw	Driver	General Underground	11-May-1992	Tower Exposure Data
Tower	0.19	Bagshaw	Driver	General Underground	21-May-1992	Tower Exposure Data
Tower	0.12	Bagshaw	Driver	Panel	12-Jun-1992	Tower Exposure Data
Tower	0.46	Bagshaw	Driver	Transport Roads	14-Dec-1992	Tower Exposure Data
Tower	0.10	Bagshaw	Driver	General Underground	09-Feb-1993	Tower Exposure Data
Tower	0.34	Bagshaw	Driver	Longwall	12-Mar-1993	Fuel Trials
Tower	0.26	Bobcat	Driver	Panel	22-Aug-1991	Tower Exposure Data
Tower	0.07	Bobcat	Driver	General Underground	10-Feb-1992	Tower Exposure Data
Tower	0.43	Bobcat	Driver	Panel	15-Feb-1993	Tower Exposure Data
Tower	0.21	Bobcat	Driver	General Underground	15-Feb-1993	Tower Exposure Data
Tower	0.22	Bobcat	Driver	Transport Roads	16-Feb-1993	Tower Exposure Data
Tower	0.27	Chock Transporter	Driver	Transport Roads	21-Aug-1990	Tower Exposure Data
Tower	0.11	Chock Transporter	Driver	General Underground	21-Aug-1990	Tower Exposure Data

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.45	Chock Transporter	Driver	Longwall	22-Aug-1990	Tower Exposure Data
Tower	0.32	Chock Transporter	Driver	Longwall	10-Apr-1991	Tower Exposure Data
Tower	0.53	Chock Transporter	Driver	Longwall	17-Jul-1991	Tower Exposure Data
Tower	0.25	Chock Transporter	Driver	Longwall	19-Nov-1992	Tower Exposure Data
Tower	0.51	Chock Transporter	Driver	Longwall	19-Nov-1992	Tower Exposure Data
Tower	0.17	Chock Transporter	Driver	Longwall	25-Nov-1992	Tower Exposure Data
Tower	0.26	Chock Transporter	Driver	Longwall	01-Dec-1992	Tower Exposure Data
Tower	0.12	Chock Transporter	Driver	Longwall	01-Aug-1995	Tower Exposure Data
Tower	0.24	Chock Transporter	Driver	Longwall	01-Aug-1995	Tower Exposure Data
Tower	0.17	Chock Transporter	Driver	Longwall	02-Aug-1995	Tower Exposure Data
Tower	0.17	Chock Transporter	Driver	Longwall	02-Aug-1995	Tower Exposure Data
Tower	0.24	Chock Transporter	Driver	Longwall	03-Aug-1995	Tower Exposure Data
Tower	0.24	Chock Transporter	Driver	Longwall	03-Aug-1995	Tower Exposure Data
Tower	0.16	Chock Transporter	Driver	Longwall	03-Aug-1995	Tower Exposure Data
Tower	0.16	Chock Transporter	Driver	Longwall	03-Aug-1995	Tower Exposure Data
Tower	0.14	Chock Transporter	Driver	Longwall	04-Aug-1995	Tower Exposure Data
Tower	0.21	Chock Transporter	Driver	Longwall	04-Aug-1995	Tower Exposure Data
Tower	0.26	Chock Transporter	Driver	Longwall	22-Aug-1995	Tower Exposure Data
Tower	0.26	Chock Transporter	Driver	Longwall	22-Aug-1995	Tower Exposure Data
Tower	0.15	Chock Transporter	Driver	Longwall	23-Aug-1995	Tower Exposure Data
Tower	0.39	Chock Transporter	Driver	Longwall	24-Aug-1995	Tower Exposure Data
Tower	0.25	Chock Transporter	Driver	Longwall	24-Aug-1995	Tower Exposure Data
Tower	0.17	Domino	Driver	Transport Roads	23-Aug-1990	Tower Exposure Data
Tower	0.13	Domino	Driver	Transport Roads	11-Feb-1991	Tower Exposure Data
Tower	0.23	Domino	Driver	Transport Roads	18-Apr-1991	Tower Exposure Data
Tower	0.28	Domino	Driver	Panel	03-May-1991	Tower Exposure Data

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.33	Domino	Driver	Panel	17-May-1991	Tower Exposure Data
Tower	0.22	Domino	Driver	Longwall	30-May-1991	Tower Exposure Data
Tower	0.25	Domino	Driver	Longwall	30-May-1991	Tower Exposure Data
Tower	0.10	Domino	Driver	Panel	13-Jun-1991	Tower Exposure Data
Tower	0.20	Domino	Driver	General Underground	18-Sep-1991	Tower Exposure Data
Tower	0.31	Domino	Driver	General Underground	18-Sep-1991	Tower Exposure Data
Tower	0.13	Domino	General Hand	Transport Roads	03-Oct-1991	Tower Exposure Data
Tower	0.14	Domino	Driver	Panel	24-Apr-1992	Tower Exposure Data
Tower	0.18	Domino	Driver	Panel	27-Apr-1992	Tower Exposure Data
Tower	0.08	Domino	Driver	Panel	07-May-1992	Tower Exposure Data
Tower	0.18	Domino	Driver	General Underground	11-May-1992	Tower Exposure Data
Tower	0.14	Domino	Driver	Panel	15-May-1992	Tower Exposure Data
Tower	0.19	Domino	Driver	Panel	21-May-1992	Tower Exposure Data
Tower	0.14	Domino	Driver	General Underground	01-Jun-1992	Tower Exposure Data
Tower	0.13	Domino	Driver	General Underground	01-Jun-1992	Tower Exposure Data
Tower	0.22	Domino	Driver	General Underground	12-Jun-1992	Tower Exposure Data
Tower	0.21	Domino	General Hand	General Underground	12-Jun-1992	Tower Exposure Data
Tower	0.13	Domino	Driver	Longwall	14-Dec-1992	Tower Exposure Data
Tower	0.22	EIMCO 913	Driver	Transport Roads	21-Aug-1990	Tower Exposure Data
Tower	0.55	EIMCO 913	Driver	Longwall	22-Aug-1990	Tower Exposure Data
Tower	0.25	EIMCO 913	Driver	Transport Roads	23-Aug-1990	Tower Exposure Data
Tower	0.48	EIMCO 913	Driver	Longwall	02-Apr-1991	Tower Exposure Data
Tower	0.26	EIMCO 913	Driver	Longwall	02-Apr-1991	Tower Exposure Data
Tower	0.35	EIMCO 913	Driver	Longwall	10-Apr-1991	Tower Exposure Data
Tower	0.16	EIMCO 913	Driver	Longwall	12-Apr-1991	Tower Exposure Data
Tower	0.59	EIMCO 913	Driver	Transport Roads	24-Apr-1991	Tower Exposure Data

Mine	DP Concentration (mg/m³)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.31	EIMCO 913	Driver	Panel	17-May-1991	Tower Exposure Data
Tower	0.24	EIMCO 913	Driver	Panel	17-May-1991	Tower Exposure Data
Tower	0.07	EIMCO 913	Driver	Longwall	15-Jul-1991	Tower Exposure Data
Tower	0.30	EIMCO 913	Driver	General Underground	22-Aug-1991	Tower Exposure Data
Tower	0.32	EIMCO 913	Driver	Panel	18-Sep-1991	Tower Exposure Data
Tower	0.25	EIMCO 913	Driver	Transport Roads	27-Sep-1991	Tower Exposure Data
Tower	0.08	EIMCO 913	Driver	General Underground	03-Oct-1991	Tower Exposure Data
Tower	0.18	EIMCO 913	Driver	General Underground	10-Feb-1992	Tower Exposure Data
Tower	0.19	EIMCO 913	Driver	Panel	24-Apr-1992	Tower Exposure Data
Tower	0.21	EIMCO 913	Driver	Panel	01-May-1992	Tower Exposure Data
Tower	0.21	EIMCO 913	Driver	Longwall	07-May-1992	Tower Exposure Data
Tower	0.10	EIMCO 913	Driver	General Underground	13-May-1992	Tower Exposure Data
Tower	0.19	EIMCO 913	Driver	General Underground	10-Jun-1992	Tower Exposure Data
Tower	0.12	EIMCO 913	Driver	General Underground	12-Jun-1992	Tower Exposure Data
Tower	0.20	EIMCO 913	Driver	Transport Roads	24-Nov-1992	Tower Exposure Data
Tower	0.26	EIMCO 913	Driver	Transport Roads	11-Feb-1993	Tower Exposure Data
Tower	0.13	EIMCO 913	Driver	Panel	15-Feb-1993	Tower Exposure Data
Tower	0.20	EIMCO 913	Driver	Longwall	16-Feb-1993	Tower Exposure Data
Tower	0.11	EIMCO 913	Driver	Panel	11-Mar-1993	Fuel Trials
Tower	0.30	EIMCO 913	Driver	Transport Roads	12-Mar-1993	Fuel Trials
Tower	0.08	EIMCO 913	Driver	General Underground	22-Mar-1993	Fuel Trials
Tower	0.10	EIMCO 913	Driver	Longwall	26-Jul-1995	Tower Exposure Data
Tower	0.09	EIMCO 913	Nil Personnel	Longwall	26-Jul-1995	Tower Exposure Data
Tower	0.11	EIMCO 913	Nil Personnel	Longwall	28-Jul-1995	Tower Exposure Data
Tower	0.10	EIMCO 913	Driver	Longwall	28-Jul-1995	Tower Exposure Data
Tower	0.20	EIMCO 913	Driver	Longwall	08-Aug-1995	Tower Exposure Data

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.22	EIMCO 913	Nil Personnel	Longwall	08-Aug-1995	Tower Exposure Data
Tower	0.19	EIMCO 913	Nil Personnel	General Underground	31-Aug-1995	Tower Exposure Data
Tower	0.17	EIMCO 913	Driver	General Underground	31-Aug-1995	Tower Exposure Data
Tower	0.20	Grader	Driver	General Underground	24-Apr-1991	Tower Exposure Data
Tower	0.11	Grader	Driver	General Underground	10-May-1992	Tower Exposure Data
Tower	0.12	Grader	Driver	Transport Roads	13-May-1992	Tower Exposure Data
Tower	0.16	Grader	Driver	General Underground	11-Feb-1993	Tower Exposure Data
Tower	0.11	MPV	Driver	Longwall	02-Apr-1991	Tower Exposure Data
Tower	0.19	MPV	Driver	Longwall	02-Apr-1991	Tower Exposure Data
Tower	0.09	MPV	Driver	General Underground	18-Apr-1991	Tower Exposure Data
Tower	0.17	MPV	Driver	General Underground	30-May-1991	Tower Exposure Data
Tower	0.25	MPV	Driver	General Underground	30-May-1991	Tower Exposure Data
Tower	0.12	MPV	Driver	Panel	13-Jun-1991	Tower Exposure Data
Tower	0.07	MPV	Driver	Transport Roads	05-Jul-1991	Tower Exposure Data
Tower	0.18	MPV	Driver	General Underground	15-Jul-1991	Tower Exposure Data
Tower	0.32	MPV	Driver	Transport Roads	17-Jul-1991	Tower Exposure Data
Tower	0.24	MPV	Driver	General Underground	18-Jul-1991	Tower Exposure Data
Tower	0.08	MPV	Driver	General Underground	22-Aug-1991	Tower Exposure Data
Tower	0.12	MPV	Driver	General Underground	22-Aug-1991	Tower Exposure Data
Tower	0.24	MPV	Driver	Transport Roads	18-Sep-1991	Tower Exposure Data
Tower	0.31	MPV	Driver	Transport Roads	18-Sep-1991	Tower Exposure Data
Tower	0.16	MPV	Driver	Transport Roads	27-Sep-1991	Tower Exposure Data
Tower	0.24	MPV	Driver	Transport Roads	27-Sep-1991	Tower Exposure Data
Tower	0.16	MPV	Driver	General Underground	24-Apr-1992	Tower Exposure Data
Tower	0.20	MPV	Driver	Longwall	18-Nov-1992	Tower Exposure Data
Tower	0.20	MPV	Driver	Transport Roads	09-Feb-1993	Tower Exposure Data

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.09	MPV	Driver	General Underground	09-Feb-1993	Tower Exposure Data
Tower	0.11	MPV	Driver	General Underground	11-Feb-1993	Tower Exposure Data
Tower	0.38	MPV	Driver	General Underground	16-Feb-1993	Tower Exposure Data
Tower	0.79	MPV	Driver	General Underground	16-Feb-1993	Tower Exposure Data
Tower	0.17	MPV	Driver	Transport Roads	10-Mar-1993	Fuel Trials
Tower	0.23	MPV	Driver	Transport Roads	10-Mar-1993	Fuel Trials
Tower	0.20	MPV	Driver	Transport Roads	10-Mar-1993	Fuel Trials
Tower	0.10	MPV	Driver	Transport Roads	11-Mar-1993	Fuel Trials
Tower	0.21	MPV	Driver	Transport Roads	11-Mar-1993	Fuel Trials
Tower	0.10	MPV	Driver	Transport Roads	11-Mar-1993	Fuel Trials
Tower	0.24	MPV	Driver	Transport Roads	12-Mar-1993	Fuel Trials
Tower	0.08	MPV	Driver	General Underground	17-Mar-1993	Fuel Trials
Tower	0.06	MPV	Driver	Transport Roads	17-Mar-1993	Fuel Trials
Tower	0.06	MPV	Driver	General Underground	17-Mar-1993	Fuel Trials
Tower	0.21	MPV	Driver	Panel	19-Mar-1993	Fuel Trials
Tower	0.17	MPV	Driver	Panel	19-Mar-1993	Fuel Trials
Tower	0.29	MPV	Driver	Transport Roads	22-Mar-1993	Fuel Trials
Tower	0.08	MPV	Driver	General Underground	23-Mar-1993	Fuel Trials
Tower	0.25	MPV	Driver	Longwall	23-Mar-1993	Fuel Trials
Tower	0.22	MPV	Driver	Longwall	23-Mar-1993	Fuel Trials
Tower	0.51	MPV	Driver	General Underground	24-Mar-1993	Fuel Trials
Tower	0.51	MPV	Driver	General Underground	24-Mar-1993	Fuel Trials
Tower	0.35	Nil Machine	General Hand	Longwall	22-Aug-1990	Tower Exposure Data
Tower	0.23	Nil Machine	General Hand	Longwall	22-Aug-1990	Tower Exposure Data
Tower	0.12	Nil Machine	General Hand	General Underground	11-Feb-1991	Tower Exposure Data
Tower	0.05	Nil Machine	General Hand	General Underground	11-Feb-1991	Tower Exposure Data

Mine	DP Concentration (mg/m³)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.33	Nil Machine	General Hand	General Underground	11-Feb-1991	Tower Exposure Data
Tower	0.21	Nil Machine	General Hand	Longwall	02-Apr-1991	Tower Exposure Data
Tower	0.44	Nil Machine	General Hand	Longwall	10-Apr-1991	Tower Exposure Data
Tower	0.28	Nil Machine	General Hand	Longwall	10-Apr-1991	Tower Exposure Data
Tower	0.60	Nil Machine	General Hand	Longwall	10-Apr-1991	Tower Exposure Data
Tower	0.22	Nil Machine	General Hand	Longwall	12-Apr-1991	Tower Exposure Data
Tower	0.08	Nil Machine	General Hand	Transport Roads	18-Apr-1991	Tower Exposure Data
Tower	0.16	Nil Machine	General Hand	Transport Roads	18-Apr-1991	Tower Exposure Data
Tower	0.14	Nil Machine	General Hand	Transport Roads	18-Apr-1991	Tower Exposure Data
Tower	0.14	Nil Machine	General Hand	Panel	03-May-1991	Tower Exposure Data
Tower	0.20	Nil Machine	General Hand	Panel	08-May-1991	Tower Exposure Data
Tower	0.10	Nil Machine	General Hand	Panel	08-May-1991	Tower Exposure Data
Tower	0.10	Nil Machine	General Hand	Panel	08-May-1991	Tower Exposure Data
Tower	0.11	Nil Machine	General Hand	Panel	08-May-1991	Tower Exposure Data
Tower	0.20	Nil Machine	General Hand	Panel	17-May-1991	Tower Exposure Data
Tower	0.19	Nil Machine	General Hand	General Underground	17-May-1991	Tower Exposure Data
Tower	0.14	Nil Machine	General Hand	Panel	13-Jun-1991	Tower Exposure Data
Tower	0.12	Nil Machine	General Hand	Panel	13-Jun-1991	Tower Exposure Data
Tower	0.11	Nil Machine	General Hand	Panel	18-Jun-1991	Tower Exposure Data
Tower	0.12	Nil Machine	General Hand	Panel	18-Jun-1991	Tower Exposure Data
Tower	0.11	Nil Machine	General Hand	Panel	18-Jun-1991	Tower Exposure Data
Tower	0.11	Nil Machine	General Hand	Panel	18-Jun-1991	Tower Exposure Data
Tower	0.19	Nil Machine	General Hand	Transport Roads	06-Jul-1991	Tower Exposure Data
Tower	0.16	Nil Machine	General Hand	Transport Roads	06-Jul-1991	Tower Exposure Data
Tower	0.06	Nil Machine	General Hand	Longwall	15-Jul-1991	Tower Exposure Data
Tower	0.13	Nil Machine	General Hand	Longwall	17-Jul-1991	Tower Exposure Data

Mine	DP Concentration (mg/m³)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.28	Nil Machine	General Hand	Longwall	18-Jul-1991	Tower Exposure Data
Tower	0.20	Nil Machine	General Hand	Longwall	18-Jul-1991	Tower Exposure Data
Tower	0.07	Nil Machine	General Hand	Transport Roads	03-Oct-1991	Tower Exposure Data
Tower	0.11	Nil Machine	General Hand	Transport Roads	03-Oct-1991	Tower Exposure Data
Tower	0.06	Nil Machine	General Hand	General Underground	03-Oct-1991	Tower Exposure Data
Tower	0.16	Nil Machine	General Hand	Panel	24-Apr-1992	Tower Exposure Data
Tower	0.11	Nil Machine	General Hand	Panel	24-Apr-1992	Tower Exposure Data
Tower	0.15	Nil Machine	General Hand	Panel	27-Apr-1992	Tower Exposure Data
Tower	0.15	Nil Machine	General Hand	Panel	27-Apr-1992	Tower Exposure Data
Tower	0.15	Nil Machine	General Hand	Panel	27-Apr-1992	Tower Exposure Data
Tower	0.14	Nil Machine	General Hand	Panel	27-Apr-1992	Tower Exposure Data
Tower	0.04	Nil Machine	General Hand	Panel	29-Apr-1992	Tower Exposure Data
Tower	0.10	Nil Machine	General Hand	General Underground	29-Apr-1992	Tower Exposure Data
Tower	0.06	Nil Machine	General Hand	Panel	29-Apr-1992	Tower Exposure Data
Tower	0.09	Nil Machine	General Hand	Panel	01-May-1992	Tower Exposure Data
Tower	0.18	Nil Machine	General Hand	Panel	01-May-1992	Tower Exposure Data
Tower	0.09	Nil Machine	General Hand	Panel	01-May-1992	Tower Exposure Data
Tower	0.14	Nil Machine	General Hand	Panel	04-May-1992	Tower Exposure Data
Tower	0.10	Nil Machine	General Hand	Panel	04-May-1992	Tower Exposure Data
Tower	0.13	Nil Machine	General Hand	Panel	04-May-1992	Tower Exposure Data
Tower	0.10	Nil Machine	General Hand	General Underground	04-May-1992	Tower Exposure Data
Tower	0.14	Nil Machine	General Hand	General Underground	04-May-1992	Tower Exposure Data
Tower	0.07	Nil Machine	General Hand	Panel	07-May-1992	Tower Exposure Data
Tower	0.21	Nil Machine	General Hand	General Underground	11-May-1992	Tower Exposure Data
Tower	0.06	Nil Machine	General Hand	Panel	13-May-1992	Tower Exposure Data
Tower	0.06	Nil Machine	General Hand	General Underground	13-May-1992	Tower Exposure Data

Mine	DP Concentration (mg/m³)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.07	Nil Machine	General Hand	Panel	13-May-1992	Tower Exposure Data
Tower	0.21	Nil Machine	General Hand	Panel	21-May-1992	Tower Exposure Data
Tower	0.20	Nil Machine	General Hand	Panel	21-May-1992	Tower Exposure Data
Tower	0.23	Nil Machine	General Hand	Panel	21-May-1992	Tower Exposure Data
Tower	0.11	Nil Machine	General Hand	General Underground	28-May-1992	Tower Exposure Data
Tower	0.41	Nil Machine	General Hand	General Underground	28-May-1992	Tower Exposure Data
Tower	0.14	Nil Machine	General Hand	Transport Roads	28-May-1992	Tower Exposure Data
Tower	0.11	Nil Machine	General Hand	Transport Roads	28-May-1992	Tower Exposure Data
Tower	0.12	Nil Machine	General Hand	General Underground	28-May-1992	Tower Exposure Data
Tower	0.11	Nil Machine	General Hand	General Underground	01-Jun-1992	Tower Exposure Data
Tower	0.08	Nil Machine	General Hand	General Underground	10-Jun-1992	Tower Exposure Data
Tower	0.15	Nil Machine	General Hand	General Underground	10-Jun-1992	Tower Exposure Data
Tower	0.14	Nil Machine	General Hand	General Underground	10-Jun-1992	Tower Exposure Data
Tower	0.10	Nil Machine	General Hand	General Underground	10-Jun-1992	Tower Exposure Data
Tower	0.17	Nil Machine	General Hand	Panel	12-Jun-1992	Tower Exposure Data
Tower	0.14	Nil Machine	General Hand	Longwall	19-Nov-1992	Tower Exposure Data
Tower	0.17	Nil Machine	General Hand	Longwall	24-Nov-1992	Tower Exposure Data
Tower	0.15	Nil Machine	General Hand	Longwall	24-Nov-1992	Tower Exposure Data
Tower	0.19	Nil Machine	General Hand	Longwall	24-Nov-1992	Tower Exposure Data
Tower	0.14	Nil Machine	General Hand	Longwall	24-Nov-1992	Tower Exposure Data
Tower	0.16	Nil Machine	General Hand	Longwall	25-Nov-1992	Tower Exposure Data
Tower	0.22	Nil Machine	General Hand	Longwall	25-Nov-1992	Tower Exposure Data
Tower	0.20	Nil Machine	General Hand	Longwall	25-Nov-1992	Tower Exposure Data
Tower	0.11	Nil Machine	General Hand	Longwall	26-Nov-1992	Tower Exposure Data
Tower	0.24	Nil Machine	General Hand	Longwall	26-Nov-1992	Tower Exposure Data
Tower	0.15	Nil Machine	General Hand	Longwall	26-Nov-1992	Tower Exposure Data

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.16	Nil Machine	General Hand	Longwall	26-Nov-1992	Tower Exposure Data
Tower	0.18	Nil Machine	General Hand	Longwall	26-Nov-1992	Tower Exposure Data
Tower	0.13	Nil Machine	General Hand	Longwall	01-Dec-1992	Tower Exposure Data
Tower	0.13	Nil Machine	General Hand	Longwall	01-Dec-1992	Tower Exposure Data
Tower	0.13	Nil Machine	General Hand	Longwall	01-Dec-1992	Tower Exposure Data
Tower	0.30	Nil Machine	General Hand	Transport Roads	08-Dec-1992	Tower Exposure Data
Tower	0.09	Nil Machine	General Hand	Transport Roads	08-Dec-1992	Tower Exposure Data
Tower	0.23	Nil Machine	General Hand	Longwall	14-Dec-1992	Tower Exposure Data
Tower	0.35	Nil Machine	General Hand	Transport Roads	14-Dec-1992	Tower Exposure Data
Tower	0.28	Nil Machine	General Hand	Longwall	14-Dec-1992	Tower Exposure Data
Tower	0.22	Nil Machine	General Hand	Transport Roads	11-Feb-1993	Tower Exposure Data
Tower	0.19	Nil Machine	General Hand	Panel	15-Feb-1993	Tower Exposure Data
Tower	0.11	Nil Machine	Nil Personnel	Longwall	23-Aug-1995	Tower Exposure Data
Tower	0.14	Nil Machine	Nil Personnel	Longwall	23-Aug-1995	Tower Exposure Data
Tower	0.22	PJB	Driver	Transport Roads	27-Sep-1991	Tower Exposure Data
Tower	0.17	PJB	Driver	Transport Roads	27-Sep-1991	Tower Exposure Data
Tower	0.15	PJB	Driver	General Underground	10-Feb-1992	Tower Exposure Data
Tower	0.09	PJB	Driver	General Underground	29-Apr-1992	Tower Exposure Data
Tower	0.08	PJB	Driver	General Underground	01-May-1992	Tower Exposure Data
Tower	0.53	PJB	Driver	Transport Roads	09-Feb-1993	Tower Exposure Data
Tower	0.17	PJB	Driver	Transport Roads	11-Feb-1993	Tower Exposure Data
Tower	0.13	PJB	Driver	Transport Roads	10-Mar-1993	Fuel Trials
Tower	0.06	PJB	Driver	Transport Roads	11-Mar-1993	Fuel Trials
Tower	0.40	PJB	Driver	Transport Roads	12-Mar-1993	Fuel Trials
Tower	0.10	PJB	Driver	Transport Roads	17-Mar-1993	Fuel Trials
Tower	0.09	PJB	Driver	Transport Roads	17-Mar-1993	Fuel Trials

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.07	PJB	Driver	General Underground	19-Mar-1993	Fuel Trials
Tower	0.09	PJB	Driver	Transport Roads	19-Mar-1993	Fuel Trials
Tower	0.03	PJB	Driver	General Underground	22-Mar-1993	Fuel Trials
Tower	0.04	PJB	Driver	General Underground	23-Mar-1993	Fuel Trials
Tower	0.08	PJB	Driver	General Underground	24-Mar-1993	Fuel Trials
Tower	0.39	Shearer Transporter	Driver	Transport Roads	08-Dec-1992	Tower Exposure Data
Tower	2.16	Shearer Transporter	Driver	Transport Roads	08-Dec-1992	Tower Exposure Data
Tower	0.15	Wagner	Driver	Longwall	07-May-1992	Tower Exposure Data
Tower	0.23	Wagner	Driver	Longwall	19-Nov-1992	Tower Exposure Data
Tower	0.14	Wagner	Driver	Longwall	01-Dec-1992	Tower Exposure Data
Tower	0.14	Wagner	Driver	Transport Roads	07-Dec-1992	Tower Exposure Data
Tower	0.05	Wagner	Driver	Panel	22-Mar-1993	Fuel Trials
Tower	0.25	Wagner	Driver	Longwall	24-Aug-1995	Tower Exposure Data
Ulan	0.20	EIMCO 913	Driver	Transport Roads	20-Jul-1994	ACARP Exposure Data
Ulan	0.17	EIMCO 913	Driver	General Underground	20-Jul-1994	ACARP Exposure Data
Ulan	0.31	EIMCO 913	Driver	Transport Roads	20-Jul-1994	ACARP Exposure Data
Ulan	0.15	EIMCO 913	Driver	General Underground	22-Jul-1994	ACARP Exposure Data
Ulan	0.16	EIMCO 913	Driver	Transport Roads	27-Jul-1994	ACARP Exposure Data
Ulan	0.31	EIMCO 913	Driver	General Underground	18-Aug-1994	ACARP Exposure Data
Ulan	0.30	EIMCO 913	Driver	General Underground	18-Aug-1994	ACARP Exposure Data
Ulan	0.26	EIMCO 913	Driver	Transport Roads	19-Aug-1994	ACARP Exposure Data
Ulan	0.16	EIMCO 913	Driver	General Underground	19-Aug-1994	ACARP Exposure Data
Ulan	0.18	Grader	Driver	Transport Roads	20-Jul-1994	ACARP Exposure Data
Ulan	0.18	Grader	Driver	Transport Roads	21-Jul-1994	ACARP Exposure Data
Ulan	0.16	Grader	Driver	Transport Roads	22-Jul-1994	ACARP Exposure Data
Ulan	0.20	Grader	Driver	Transport Roads	27-Jul-1994	ACARP Exposure Data

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Ulan	0.30	Grader	Driver	Transport Roads	18-Aug-1994	ACARP Exposure Data
Ulan	0.23	PET	Driver	General Underground	27-Jul-1994	ACARP Exposure Data
Ulan	0.19	PJB	Driver	Transport Roads	19-Aug-1994	ACARP Exposure Data
West Walsend	0.14	EIMCO 912	Driver	General Underground	06-Dec-1994	ACARP Exposure Data
West Walsend	0.15	EIMCO 912	Driver	General Underground	07-Dec-1994	ACARP Exposure Data
West Walsend	0.17	EIMCO 913	Driver	Transport Roads	08-Dec-1994	ACARP Exposure Data
West Walsend	0.17	EIMCO 913	Driver	Transport Roads	08-Dec-1994	ACARP Exposure Data
West Walsend	0.17	EIMCO 913	Driver	Transport Roads	09-Dec-1994	ACARP Exposure Data
West Walsend	0.15	EIMCO 913	Driver	General Underground	14-Dec-1994	ACARP Exposure Data
West Walsend	0.14	EIMCO 913	Driver	General Underground	14-Dec-1994	ACARP Exposure Data
West Walsend	0.25	EIMCO 936	Driver	Transport Roads	08-Dec-1994	ACARP Exposure Data
West Walsend	0.20	EIMCO 936	Driver	Transport Roads	09-Dec-1994	ACARP Exposure Data
West Walsend	0.09	Grader	Driver	General Underground	06-Dec-1994	ACARP Exposure Data
West Walsend	0.62	Grader	Driver	Transport Roads	14-Dec-1994	ACARP Exposure Data
West Walsend	0.12	Nil Machine	General Hand	General Underground	06-Dec-1994	ACARP Exposure Data
West Walsend	0.06	Nil Machine	General Hand	General Underground	07-Dec-1994	ACARP Exposure Data
West Walsend	0.10	PJB	Driver	General Underground	06-Dec-1994	ACARP Exposure Data
West Walsend	0.16	PJB	Driver	General Underground	07-Dec-1994	ACARP Exposure Data
West Walsend	0.06	PJB	Driver	General Underground	09-Dec-1994	ACARP Exposure Data
West Walsend	0.07	PJB	Driver	Transport Roads	14-Dec-1994	ACARP Exposure Data
West Cliff	0.14	Domino	Driver	General Underground	22-Aug-1994	ACARP Exposure Data
West Cliff	0.07	Domino	Driver	Transport Roads	22-Aug-1994	ACARP Exposure Data
West Cliff	0.08	Domino	Driver	Transport Roads	23-Aug-1994	ACARP Exposure Data
West Cliff	0.03	Domino	Driver	Transport Roads	23-Aug-1994	ACARP Exposure Data
West Cliff	0.04	Domino	Driver	General Underground	23-Aug-1994	ACARP Exposure Data
West Cliff	0.08	Domino	Driver	General Underground	24-Aug-1994	ACARP Exposure Data

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
West Cliff	0.10	Domino	Driver	Transport Roads	24-Aug-1994	ACARP Exposure Data
West Cliff	0.12	Domino	Driver	General Underground	24-Aug-1994	ACARP Exposure Data
West Cliff	0.10	Domino	Driver	Transport Roads	25-Aug-1994	ACARP Exposure Data
West Cliff	0.10	Domino	Driver	General Underground	25-Aug-1994	ACARP Exposure Data
West Cliff	0.05	Domino	Driver	General Underground	26-Aug-1994	ACARP Exposure Data
West Cliff	0.07	Domino	Driver	Transport Roads	26-Aug-1994	ACARP Exposure Data
West Cliff	0.08	Domino	Driver	Transport Roads	26-Aug-1994	ACARP Exposure Data
West Cliff	0.16	Domino	Driver	General Underground	29-Aug-1994	ACARP Exposure Data
West Cliff	0.09	Domino	Driver	Transport Roads	29-Aug-1994	ACARP Exposure Data
West Cliff	0.08	Domino	Driver	Transport Roads	29-Aug-1994	ACARP Exposure Data
West Cliff	0.10	Domino	Driver	Transport Roads	25-Aug-1997	ACARP Exposure Data
West Cliff	0.10	EIMCO 913	Driver	Transport Roads	22-Aug-1994	ACARP Exposure Data
West Cliff	0.14	Grader	Driver	General Underground	22-Aug-1994	ACARP Exposure Data
West Cliff	0.11	Grader	Driver	Transport Roads	23-Aug-1994	ACARP Exposure Data
West Cliff	0.17	Grader	Driver	Transport Roads	24-Aug-1994	ACARP Exposure Data
West Cliff	0.07	Grader	Driver	Transport Roads	25-Aug-1994	ACARP Exposure Data
West Cliff	0.09	Grader	Driver	Transport Roads	26-Aug-1994	ACARP Exposure Data
West Cliff	0.10	Grader	Driver	Transport Roads	29-Aug-1994	ACARP Exposure Data

APPENDIX 2

TOWER COLLIERY RESEARCH GROUP

TEST TUNNEL DATA

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.63	EIMCO 913	Nil Personnel	Tower Test Tunnel	03-Mar-1995	Exhaust Filters
Tower	0.73	EIMCO 913	Driver	Tower Test Tunnel	03-Mar-1995	Exhaust Filters
Tower	1.18	EIMCO 913	Nil Personnel	Tower Test Tunnel	03-Mar-1995	Exhaust Filters
Tower	0.31	EIMCO 913	Nil Personnel	Tower Test Tunnel	03-Mar-1995	Exhaust Filters
Tower	0.66	EIMCO 913	Driver	Tower Test Tunnel	06-Mar-1995	Exhaust Filters
Tower	0.70	EIMCO 913	Nil Personnel	Tower Test Tunnel	06-Mar-1995	Exhaust Filters
Tower	1.12	EIMCO 913	Nil Personnel	Tower Test Tunnel	06-Mar-1995	Exhaust Filters
Tower	0.14	EIMCO 913	Nil Personnel	Tower Test Tunnel	06-Mar-1995	Exhaust Filters
Tower	0.19	EIMCO 913	Nil Personnel	Tower Test Tunnel	07-Mar-1995	Exhaust Filters
Tower	0.07	EIMCO 913	Nil Personnel	Tower Test Tunnel	07-Mar-1995	Exhaust Filters
Tower	0.10	EIMCO 913	Driver	Tower Test Tunnel	07-Mar-1995	Exhaust Filters
Tower	0.07	EIMCO 913	Nil Personnel	Tower Test Tunnel	07-Mar-1995	Exhaust Filters
Tower	0.07	EIMCO 913	Driver	Tower Test Tunnel	08-Mar-1995	Exhaust Filters
Tower	0.01	EIMCO 913	Nil Personnel	Tower Test Tunnel	08-Mar-1995	Exhaust Filters
Tower	0.12	EIMCO 913	Driver	Tower Test Tunnel	08-Mar-1995	Exhaust Filters
Tower	0.17	EIMCO 913	Nil Personnel	Tower Test Tunnel	08-Mar-1995	Exhaust Filters
Tower	0.12	EIMCO 913	Nil Personnel	Tower Test Tunnel	08-Mar-1995	Exhaust Filters
Tower	0.19	EIMCO 913	Nil Personnel	Tower Test Tunnel	08-Mar-1995	Exhaust Filters
Tower	0.03	EIMCO 913	Nil Personnel	Tower Test Tunnel	08-Mar-1995	Exhaust Filters
Tower	0.15	EIMCO 913	Nil Personnel	Tower Test Tunnel	08-Mar-1995	Exhaust Filters
Tower	0.23	EIMCO 913	Nil Personnel	Tower Test Tunnel	09-Mar-1995	Exhaust Filters
Tower	0.05	EIMCO 913	Nil Personnel	Tower Test Tunnel	09-Mar-1995	Exhaust Filters
Tower	0.17	EIMCO 913	Nil Personnel	Tower Test Tunnel	09-Mar-1995	Exhaust Filters
Tower	0.10	EIMCO 913	Nil Personnel	Tower Test Tunnel	09-Mar-1995	Exhaust Filters
Tower	0.08	EIMCO 913	Nil Personnel	Tower Test Tunnel	09-Mar-1995	Exhaust Filters

Mine	DP Concentration (mg/m³)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.12	EIMCO 913	Nil Personnel	Tower Test Tunnel	09-Mar-1995	Exhaust Filters
Tower	0.15	EIMCO 913	Driver	Tower Test Tunnel	09-Mar-1995	Exhaust Filters
Tower	0.13	EIMCO 913	Driver	Tower Test Tunnel	09-Mar-1995	Exhaust Filters
Tower	0.91	EIMCO 913	Driver	Tower Test Tunnel	28-Aug-1995	Exhaust Filters
Tower	0.34	EIMCO 913	Nil Personnel	Tower Test Tunnel	28-Aug-1995	Exhaust Filters
Tower	1.41	EIMCO 913	Nil Personnel	Tower Test Tunnel	28-Aug-1995	Exhaust Filters
Tower	0.85	EIMCO 913	Nil Personnel	Tower Test Tunnel	28-Aug-1995	Exhaust Filters
Tower	0.80	EIMCO 913	Nil Personnel	Tower Test Tunnel	30-Aug-1995	Exhaust Filters
Tower	0.18	EIMCO 913	Nil Personnel	Tower Test Tunnel	30-Aug-1995	Exhaust Filters
Tower	1.25	EIMCO 913	Nil Personnel	Tower Test Tunnel	30-Aug-1995	Exhaust Filters
Tower	0.83	EIMCO 913	Driver	Tower Test Tunnel	30-Aug-1995	Exhaust Filters
Tower	0.96	EIMCO 913	Driver	Tower Test Tunnel	01-Sep-1995	Exhaust Filters
Tower	0.89	EIMCO 913	Nil Personnel	Tower Test Tunnel	01-Sep-1995	Exhaust Filters
Tower	1.57	EIMCO 913	Nil Personnel	Tower Test Tunnel	01-Sep-1995	Exhaust Filters
Tower	0.31	EIMCO 913	Nil Personnel	Tower Test Tunnel	01-Sep-1995	Exhaust Filters
Tower	0.54	MPV	Nil Personnel	Tower Test Tunnel	04-May-1994	Decoking Trials
Tower	0.28	MPV	Nil Personnel	Tower Test Tunnel	04-May-1994	Decoking Trials
Tower	0.10	MPV	Nil Personnel	Tower Test Tunnel	04-May-1994	Decoking Trials
Tower	0.28	MPV	Driver	Tower Test Tunnel	04-May-1994	Decoking Trials
Tower	0.10	MPV	Nil Personnel	Tower Test Tunnel	05-May-1994	Decoking Trials
Tower	0.50	MPV	Nil Personnel	Tower Test Tunnel	05-May-1994	Decoking Trials
Tower	0.39	MPV	Nil Personnel	Tower Test Tunnel	05-May-1994	Decoking Trials
Tower	0.33	MPV	Driver	Tower Test Tunnel	05-May-1994	Decoking Trials
Tower	0.26	MPV	Driver	Tower Test Tunnel	06-May-1994	Decoking Trials
Tower	0.11	MPV	Nil Personnel	Tower Test Tunnel	06-May-1994	Decoking Trials
Tower	0.27	MPV	Nil Personnel	Tower Test Tunnel	06-May-1994	Decoking Trials

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.46	MPV	Nil Personnel	Tower Test Tunnel	06-May-1994	Decoking Trials
Tower	0.29	MPV	Driver	Tower Test Tunnel	09-May-1994	Decoking Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	09-May-1994	Decoking Trials
Tower	0.33	MPV	Nil Personnel	Tower Test Tunnel	09-May-1994	Decoking Trials
Tower	0.54	MPV	Nil Personnel	Tower Test Tunnel	09-May-1994	Decoking Trials
Tower	0.35	MPV	Driver	Tower Test Tunnel	10-May-1994	Decoking Trials
Tower	0.12	MPV	Nil Personnel	Tower Test Tunnel	10-May-1994	Decoking Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	10-May-1994	Decoking Trials
Tower	0.15	MPV	Nil Personnel	Tower Test Tunnel	10-May-1994	Decoking Trials
Tower	0.64	MPV	Nil Personnel	Tower Test Tunnel	11-May-1994	Decoking Trials
Tower	0.36	MPV	Nil Personnel	Tower Test Tunnel	11-May-1994	Decoking Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	11-May-1994	Decoking Trials
Tower	0.44	MPV	Driver	Tower Test Tunnel	11-May-1994	Decoking Trials
Tower	0.38	MPV	Nil Personnel	Tower Test Tunnel	17-May-1994	Scrubber Tank Trials
Tower	0.24	MPV	Driver	Tower Test Tunnel	17-May-1994	Scrubber Tank Trials
Tower	0.07	MPV	Nil Personnel	Tower Test Tunnel	17-May-1994	Scrubber Tank Trials
Tower	0.18	MPV	Nil Personnel	Tower Test Tunnel	17-May-1994	Scrubber Tank Trials
Tower	0.19	MPV	Nil Personnel	Tower Test Tunnel	18-May-1994	Scrubber Tank Trials
Tower	0.27	MPV	Driver	Tower Test Tunnel	18-May-1994	Scrubber Tank Trials
Tower	0.09	MPV	Nil Personnel	Tower Test Tunnel	18-May-1994	Scrubber Tank Trials
Tower	0.32	MPV	Nil Personnel	Tower Test Tunnel	18-May-1994	Scrubber Tank Trials
Tower	0.27	MPV	Nil Personnel	Tower Test Tunnel	20-May-1994	Scrubber Tank Trials
Tower	0.15	MPV	Nil Personnel	Tower Test Tunnel	20-May-1994	Scrubber Tank Trials
Tower	0.22	MPV	Driver	Tower Test Tunnel	20-May-1994	Scrubber Tank Trials
Tower	0.06	MPV	Nil Personnel	Tower Test Tunnel	20-May-1994	Scrubber Tank Trials
Tower	0.07	MPV	Nil Personnel	Tower Test Tunnel	23-May-1994	Scrubber Tank Trials

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.24	MPV	Driver	Tower Test Tunnel	23-May-1994	Scrubber Tank Trials
Tower	0.21	MPV	Nil Personnel	Tower Test Tunnel	23-May-1994	Scrubber Tank Trials
Tower	0.31	MPV	Nil Personnel	Tower Test Tunnel	23-May-1994	Scrubber Tank Trials
Tower	0.18	MPV	Nil Personnel	Tower Test Tunnel	25-May-1994	Scrubber Tank Trials
Tower	0.33	MPV	Nil Personnel	Tower Test Tunnel	25-May-1994	Scrubber Tank Trials
Tower	0.08	MPV	Nil Personnel	Tower Test Tunnel	25-May-1994	Scrubber Tank Trials
Tower	0.25	MPV	Driver	Tower Test Tunnel	25-May-1994	Scrubber Tank Trials
Tower	0.24	MPV	Nil Personnel	Tower Test Tunnel	26-May-1994	Scrubber Tank Trials
Tower	0.08	MPV	Nil Personnel	Tower Test Tunnel	26-May-1994	Scrubber Tank Trials
Tower	0.23	MPV	Driver	Tower Test Tunnel	26-May-1994	Scrubber Tank Trials
Tower	0.30	MPV	Nil Personnel	Tower Test Tunnel	26-May-1994	Scrubber Tank Trials
Tower	0.53	MPV	Nil Personnel	Tower Test Tunnel	31-May-1994	Decoking Trials
Tower	0.46	MPV	Driver	Tower Test Tunnel	31-May-1994	Decoking Trials
Tower	0.24	MPV	Nil Personnel	Tower Test Tunnel	31-May-1994	Decoking Trials
Tower	0.67	MPV	Nil Personnel	Tower Test Tunnel	31-May-1994	Decoking Trials
Tower	0.40	MPV	Driver	Tower Test Tunnel	01-Jun-1994	Decoking Trials
Tower	0.64	MPV	Nil Personnel	Tower Test Tunnel	01-Jun-1994	Decoking Trials
Tower	0.17	MPV	Nil Personnel	Tower Test Tunnel	01-Jun-1994	Decoking Trials
Tower	0.44	MPV	Driver	Tower Test Tunnel	02-Jun-1994	Decoking Trials
Tower	0.47	MPV	Nil Personnel	Tower Test Tunnel	02-Jun-1994	Decoking Trials
Tower	0.65	MPV	Nil Personnel	Tower Test Tunnel	02-Jun-1994	Decoking Trials
Tower	0.19	MPV	Nil Personnel	Tower Test Tunnel	02-Jun-1994	Decoking Trials
Tower	0.27	MPV	Nil Personnel	Tower Test Tunnel	03-Jun-1994	Decoking Trials
Tower	0.12	MPV	Nil Personnel	Tower Test Tunnel	03-Jun-1994	Decoking Trials
Tower	0.49	MPV	Nil Personnel	Tower Test Tunnel	03-Jun-1994	Decoking Trials
Tower	0.28	MPV	Driver	Tower Test Tunnel	03-Jun-1994	Decoking Trials

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.32	MPV	Nil Personnel	Tower Test Tunnel	07-Jun-1994	Decoking Trials
Tower	0.41	MPV	Nil Personnel	Tower Test Tunnel	07-Jun-1994	Decoking Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	07-Jun-1994	Decoking Trials
Tower	0.50	MPV	Nil Personnel	Tower Test Tunnel	08-Jun-1994	Decoking Trials
Tower	0.21	MPV	Nil Personnel	Tower Test Tunnel	08-Jun-1994	Decoking Trials
Tower	0.37	MPV	Nil Personnel	Tower Test Tunnel	08-Jun-1994	Decoking Trials
Tower	0.32	MPV	Driver	Tower Test Tunnel	08-Jun-1994	Decoking Trials
Tower	0.31	MPV	Driver	Tower Test Tunnel	16-Jun-1994	Scrubber Tank Trials
Tower	0.31	MPV	Nil Personnel	Tower Test Tunnel	16-Jun-1994	Scrubber Tank Trials
Tower	0.39	MPV	Nil Personnel	Tower Test Tunnel	16-Jun-1994	Scrubber Tank Trials
Tower	0.09	MPV	Nil Personnel	Tower Test Tunnel	16-Jun-1994	Scrubber Tank Trials
Tower	0.35	MPV	Driver	Tower Test Tunnel	17-Jun-1994	Scrubber Tank Trials
Tower	0.33	MPV	Nil Personnel	Tower Test Tunnel	17-Jun-1994	Scrubber Tank Trials
Tower	0.41	MPV	Nil Personnel	Tower Test Tunnel	17-Jun-1994	Scrubber Tank Trials
Tower	0.09	MPV	Nil Personnel	Tower Test Tunnel	17-Jun-1994	Scrubber Tank Trials
Tower	0.10	MPV	Nil Personnel	Tower Test Tunnel	20-Jun-1994	Scrubber Tank Trials
Tower	0.29	MPV	Driver	Tower Test Tunnel	20-Jun-1994	Scrubber Tank Trials
Tower	0.40	MPV	Nil Personnel	Tower Test Tunnel	20-Jun-1994	Scrubber Tank Trials
Tower	0.07	MPV	Nil Personnel	Tower Test Tunnel	21-Jun-1994	Scrubber Tank Trials
Tower	0.42	MPV	Nil Personnel	Tower Test Tunnel	21-Jun-1994	Scrubber Tank Trials
Tower	0.29	MPV	Driver	Tower Test Tunnel	21-Jun-1994	Scrubber Tank Trials
Tower	0.33	MPV	Nil Personnel	Tower Test Tunnel	21-Jun-1994	Scrubber Tank Trials
Tower	0.33	MPV	Driver	Tower Test Tunnel	22-Jun-1994	Scrubber Tank Trials
Tower	0.29	MPV	Nil Personnel	Tower Test Tunnel	22-Jun-1994	Scrubber Tank Trials
Tower	0.37	MPV	Nil Personnel	Tower Test Tunnel	22-Jun-1994	Scrubber Tank Trials
Tower	0.10	MPV	Nil Personnel	Tower Test Tunnel	22-Jun-1994	Scrubber Tank Trials

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.56	MPV	Nil Personnel	Tower Test Tunnel	27-Jun-1994	Scrubber Tank Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	27-Jun-1994	Scrubber Tank Trials
Tower	0.35	MPV	Nil Personnel	Tower Test Tunnel	27-Jun-1994	Scrubber Tank Trials
Tower	0.41	MPV	Driver	Tower Test Tunnel	27-Jun-1994	Scrubber Tank Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	28-Jun-1994	Decoking Trials
Tower	0.37	MPV	Nil Personnel	Tower Test Tunnel	28-Jun-1994	Decoking Trials
Tower	0.24	MPV	Nil Personnel	Tower Test Tunnel	28-Jun-1994	Decoking Trials
Tower	0.27	MPV	Driver	Tower Test Tunnel	28-Jun-1994	Decoking Trials
Tower	0.19	MPV	Nil Personnel	Tower Test Tunnel	11-Jul-1994	Decoking Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	11-Jul-1994	Decoking Trials
Tower	0.40	MPV	Nil Personnel	Tower Test Tunnel	11-Jul-1994	Decoking Trials
Tower	0.22	MPV	Driver	Tower Test Tunnel	11-Jul-1994	Decoking Trials
Tower	0.42	MPV	Nil Personnel	Tower Test Tunnel	25-Jul-1994	Decoking Trials
Tower	0.30	MPV	Nil Personnel	Tower Test Tunnel	25-Jul-1994	Decoking Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	25-Jul-1994	Decoking Trials
Tower	0.30	MPV	Driver	Tower Test Tunnel	25-Jul-1994	Decoking Trials
Tower	0.30	MPV	Nil Personnel	Tower Test Tunnel	30-Aug-1994	Decoking Trials
Tower	0.28	MPV	Nil Personnel	Tower Test Tunnel	30-Aug-1994	Decoking Trials
Tower	0.22	MPV	Driver	Tower Test Tunnel	30-Aug-1994	Decoking Trials
Tower	0.12	MPV	Nil Personnel	Tower Test Tunnel	30-Aug-1994	Decoking Trials
Tower	0.17	MPV	Driver	Tower Test Tunnel	31-Aug-1994	Decoking Trials
Tower	0.18	MPV	Nil Personnel	Tower Test Tunnel	31-Aug-1994	Decoking Trials
Tower	0.26	MPV	Nil Personnel	Tower Test Tunnel	31-Aug-1994	Decoking Trials
Tower	0.08	MPV	Nil Personnel	Tower Test Tunnel	31-Aug-1994	Decoking Trials
Tower	0.16	MPV	Driver	Tower Test Tunnel	01-Sep-1994	Decoking Trials
Tower	0.23	MPV	Nil Personnel	Tower Test Tunnel	01-Sep-1994	Decoking Trials

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.07	MPV	Nil Personnel	Tower Test Tunnel	01-Sep-1994	Decoking Trials
Tower	0.27	MPV	Nil Personnel	Tower Test Tunnel	01-Sep-1994	Decoking Trials
Tower	0.26	MPV	Nil Personnel	Tower Test Tunnel	05-Sep-1994	Decoking Trials
Tower	0.29	MPV	Nil Personnel	Tower Test Tunnel	05-Sep-1994	Decoking Trials
Tower	0.09	MPV	Nil Personnel	Tower Test Tunnel	05-Sep-1994	Decoking Trials
Tower	0.24	MPV	Driver	Tower Test Tunnel	05-Sep-1994	Decoking Trials
Tower	0.09	MPV	Nil Personnel	Tower Test Tunnel	06-Sep-1994	Decoking Trials
Tower	0.23	MPV	Nil Personnel	Tower Test Tunnel	06-Sep-1994	Decoking Trials
Tower	0.17	MPV	Driver	Tower Test Tunnel	06-Sep-1994	Decoking Trials
Tower	0.19	MPV	Nil Personnel	Tower Test Tunnel	06-Sep-1994	Decoking Trials
Tower	0.19	MPV	Driver	Tower Test Tunnel	07-Sep-1994	Decoking Trials
Tower	0.19	MPV	Nil Personnel	Tower Test Tunnel	07-Sep-1994	Decoking Trials
Tower	0.23	MPV	Nil Personnel	Tower Test Tunnel	07-Sep-1994	Decoking Trials
Tower	0.08	MPV	Nil Personnel	Tower Test Tunnel	07-Sep-1994	Decoking Trials
Tower	0.21	MPV	Nil Personnel	Tower Test Tunnel	08-Sep-1994	Decoking Trials
Tower	0.26	MPV	Nil Personnel	Tower Test Tunnel	08-Sep-1994	Decoking Trials
Tower	0.11	MPV	Nil Personnel	Tower Test Tunnel	08-Sep-1994	Decoking Trials
Tower	0.19	MPV	Driver	Tower Test Tunnel	08-Sep-1994	Decoking Trials
Tower	0.17	MPV	Driver	Tower Test Tunnel	09-Sep-1994	Air Cleaners
Tower	0.20	MPV	Nil Personnel	Tower Test Tunnel	09-Sep-1994	Air Cleaners
Tower	0.23	MPV	Nil Personnel	Tower Test Tunnel	09-Sep-1994	Air Cleaners
Tower	0.09	MPV	Nil Personnel	Tower Test Tunnel	09-Sep-1994	Air Cleaners
Tower	0.14	MPV	Driver	Tower Test Tunnel	10-Sep-1994	Air Cleaners
Tower	0.17	MPV	Nil Personnel	Tower Test Tunnel	10-Sep-1994	Air Cleaners
Tower	0.24	MPV	Nil Personnel	Tower Test Tunnel	10-Sep-1994	Air Cleaners
Tower	0.08	MPV	Nil Personnel	Tower Test Tunnel	10-Sep-1994	Air Cleaners

Mine	DP Concentration (mg/m³)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.24	MPV	Nil Personnel	Tower Test Tunnel	12-Sep-1994	Air Cleaners
Tower	0.26	MPV	Nil Personnel	Tower Test Tunnel	12-Sep-1994	Air Cleaners
Tower	0.08	MPV	Nil Personnel	Tower Test Tunnel	12-Sep-1994	Air Cleaners
Tower	0.22	MPV	Driver	Tower Test Tunnel	12-Sep-1994	Air Cleaners
Tower	0.25	MPV	Driver	Tower Test Tunnel	13-Sep-1994	Air Cleaners
Tower	0.20	MPV	Nil Personnel	Tower Test Tunnel	13-Sep-1994	Air Cleaners
Tower	0.24	MPV	Nil Personnel	Tower Test Tunnel	13-Sep-1994	Air Cleaners
Tower	0.12	MPV	Nil Personnel	Tower Test Tunnel	13-Sep-1994	Air Cleaners
Tower	0.21	MPV	Driver	Tower Test Tunnel	13-Sep-1994	Air Cleaners
Tower	0.21	MPV	Nil Personnel	Tower Test Tunnel	13-Sep-1994	Air Cleaners
Tower	0.22	MPV	Nil Personnel	Tower Test Tunnel	13-Sep-1994	Air Cleaners
Tower	0.07	MPV	Nil Personnel	Tower Test Tunnel	13-Sep-1994	Air Cleaners
Tower	0.08	MPV	Nil Personnel	Tower Test Tunnel	14-Sep-1994	Air Cleaners
Tower	0.17	MPV	Driver	Tower Test Tunnel	14-Sep-1994	Air Cleaners
Tower	0.17	MPV	Nil Personnel	Tower Test Tunnel	14-Sep-1994	Air Cleaners
Tower	0.26	MPV	Nil Personnel	Tower Test Tunnel	14-Sep-1994	Air Cleaners
Tower	0.08	MPV	Nil Personnel	Tower Test Tunnel	15-Sep-1994	Decoking Trials
Tower	0.25	MPV	Nil Personnel	Tower Test Tunnel	15-Sep-1994	Decoking Trials
Tower	0.19	MPV	Nil Personnel	Tower Test Tunnel	15-Sep-1994	Decoking Trials
Tower	0.15	MPV	Driver	Tower Test Tunnel	15-Sep-1994	Decoking Trials
Tower	0.17	MPV	Nil Personnel	Tower Test Tunnel	27-Sep-1994	Decoking Trials
Tower	0.23	MPV	Nil Personnel	Tower Test Tunnel	27-Sep-1994	Decoking Trials
Tower	0.07	MPV	Nil Personnel	Tower Test Tunnel	27-Sep-1994	Decoking Trials
Tower	0.19	MPV	Driver	Tower Test Tunnel	27-Sep-1994	Decoking Trials
Tower	0.09	MPV	Nil Personnel	Tower Test Tunnel	28-Sep-1994	Scrubber Tank Trials
Tower	0.24	MPV	Nil Personnel	Tower Test Tunnel	28-Sep-1994	Scrubber Tank Trials

Mine	DP Concentration (mg/m³)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.20	MPV	Nil Personnel	Tower Test Tunnel	28-Sep-1994	Scrubber Tank Trials
Tower	0.19	MPV	Driver	Tower Test Tunnel	28-Sep-1994	Scrubber Tank Trials
Tower	0.10	MPV	Nil Personnel	Tower Test Tunnel	05-Oct-1994	Decoking Trials
Tower	0.26	MPV	Nil Personnel	Tower Test Tunnel	05-Oct-1994	Decoking Trials
Tower	0.19	MPV	Nil Personnel	Tower Test Tunnel	05-Oct-1994	Decoking Trials
Tower	0.17	MPV	Driver	Tower Test Tunnel	05-Oct-1994	Decoking Trials
Tower	0.11	MPV	Nil Personnel	Tower Test Tunnel	07-Oct-1994	Scrubber Tank Trials
Tower	0.28	MPV	Nil Personnel	Tower Test Tunnel	07-Oct-1994	Scrubber Tank Trials
Tower	0.19	MPV	Driver	Tower Test Tunnel	07-Oct-1994	Scrubber Tank Trials
Tower	0.25	MPV	Nil Personnel	Tower Test Tunnel	07-Oct-1994	Scrubber Tank Trials
Tower	0.19	MPV	Driver	Tower Test Tunnel	10-Oct-1994	Scrubber Tank Trials
Tower	0.10	MPV	Nil Personnel	Tower Test Tunnel	10-Oct-1994	Scrubber Tank Trials
Tower	0.24	MPV	Nil Personnel	Tower Test Tunnel	10-Oct-1994	Scrubber Tank Trials
Tower	0.16	MPV	Nil Personnel	Tower Test Tunnel	10-Oct-1994	Scrubber Tank Trials
Tower	0.16	MPV	Driver	Tower Test Tunnel	11-Oct-1994	Scrubber Tank Trials
Tower	0.18	MPV	Nil Personnel	Tower Test Tunnel	11-Oct-1994	Scrubber Tank Trials
Tower	0.10	MPV	Nil Personnel	Tower Test Tunnel	11-Oct-1994	Scrubber Tank Trials
Tower	0.22	MPV	Nil Personnel	Tower Test Tunnel	11-Oct-1994	Scrubber Tank Trials
Tower	0.14	MPV	Nil Personnel	Tower Test Tunnel	12-Oct-1994	Scrubber Tank Trials
Tower	0.25	MPV	Nil Personnel	Tower Test Tunnel	12-Oct-1994	Scrubber Tank Trials
Tower	0.22	MPV	Nil Personnel	Tower Test Tunnel	12-Oct-1994	Scrubber Tank Trials
Tower	0.18	MPV	Driver	Tower Test Tunnel	12-Oct-1994	Scrubber Tank Trials
Tower	0.10	MPV	Driver	Tower Test Tunnel	14-Oct-1994	Decoking Trials
Tower	0.17	MPV	Nil Personnel	Tower Test Tunnel	14-Oct-1994	Decoking Trials
Tower	0.24	MPV	Nil Personnel	Tower Test Tunnel	14-Oct-1994	Decoking Trials
Tower	0.08	MPV	Nil Personnel	Tower Test Tunnel	14-Oct-1994	Decoking Trials

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.21	MPV	Driver	Tower Test Tunnel	17-Oct-1994	Ventilation Trials
Tower	0.09	MPV	Nil Personnel	Tower Test Tunnel	17-Oct-1994	Ventilation Trials
Tower	0.20	MPV	Nil Personnel	Tower Test Tunnel	17-Oct-1994	Ventilation Trials
Tower	0.20	MPV	Nil Personnel	Tower Test Tunnel	17-Oct-1994	Scrubber Tank Trials
Tower	0.23	MPV	Nil Personnel	Tower Test Tunnel	17-Oct-1994	Scrubber Tank Trials
Tower	0.09	MPV	Nil Personnel	Tower Test Tunnel	17-Oct-1994	Scrubber Tank Trials
Tower	0.21	MPV	Driver	Tower Test Tunnel	17-Oct-1994	Scrubber Tank Trials
Tower	0.23	MPV	Nil Personnel	Tower Test Tunnel	17-Oct-1994	Ventilation Trials
Tower	0.15	MPV	Driver	Tower Test Tunnel	18-Oct-1994	Ventilation Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	18-Oct-1994	Ventilation Trials
Tower	0.16	MPV	Nil Personnel	Tower Test Tunnel	18-Oct-1994	Ventilation Trials
Tower	0.05	MPV	Nil Personnel	Tower Test Tunnel	18-Oct-1994	Ventilation Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	19-Oct-1994	Ventilation Trials
Tower	0.06	MPV	Nil Personnel	Tower Test Tunnel	19-Oct-1994	Ventilation Trials
Tower	0.12	MPV	Nil Personnel	Tower Test Tunnel	19-Oct-1994	Ventilation Trials
Tower	0.12	MPV	Driver	Tower Test Tunnel	19-Oct-1994	Ventilation Trials
Tower	0.14	MPV	Nil Personnel	Tower Test Tunnel	20-Oct-1994	Ventilation Trials
Tower	0.11	MPV	Nil Personnel	Tower Test Tunnel	20-Oct-1994	Ventilation Trials
Tower	0.05	MPV	Nil Personnel	Tower Test Tunnel	20-Oct-1994	Ventilation Trials
Tower	0.07	MPV	Driver	Tower Test Tunnel	20-Oct-1994	Ventilation Trials
Tower	0.10	MPV	Nil Personnel	Tower Test Tunnel	21-Oct-1994	Ventilation Trials
Tower	0.09	MPV	Nil Personnel	Tower Test Tunnel	21-Oct-1994	Ventilation Trials
Tower	0.03	MPV	Nil Personnel	Tower Test Tunnel	21-Oct-1994	Ventilation Trials
Tower	0.07	MPV	Driver	Tower Test Tunnel	21-Oct-1994	Ventilation Trials
Tower	0.08	MPV	Nil Personnel	Tower Test Tunnel	10-Nov-1994	Decoking Trials
Tower	0.18	MPV	Driver	Tower Test Tunnel	10-Nov-1994	Decoking Trials

Mine	DP Concentration (mg/m³)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.27	MPV	Nil Personnel	Tower Test Tunnel	10-Nov-1994	Decoking Trials
Tower	0.18	MPV	Driver	Tower Test Tunnel	10-Nov-1994	Decoking Trials
Tower	0.24	MPV	Nil Personnel	Tower Test Tunnel	10-Nov-1994	Decoking Trials
Tower	0.33	MPV	Nil Personnel	Tower Test Tunnel	10-Nov-1994	Decoking Trials
Tower	0.08	MPV	Nil Personnel	Tower Test Tunnel	10-Nov-1994	Decoking Trials
Tower	0.20	MPV	Nil Personnel	Tower Test Tunnel	10-Nov-1994	Decoking Trials
Tower	0.15	MPV	Driver	Tower Test Tunnel	11-Nov-1994	Ventilation Trials
Tower	0.22	MPV	Nil Personnel	Tower Test Tunnel	11-Nov-1994	Ventilation Trials
Tower	0.16	MPV	Nil Personnel	Tower Test Tunnel	11-Nov-1994	Ventilation Trials
Tower	0.11	MPV	Nil Personnel	Tower Test Tunnel	11-Nov-1994	Ventilation Trials
Tower	0.14	MPV	Nil Personnel	Tower Test Tunnel	15-Nov-1994	Ventilation Trials
Tower	0.12	MPV	Nil Personnel	Tower Test Tunnel	15-Nov-1994	Ventilation Trials
Tower	0.06	MPV	Nil Personnel	Tower Test Tunnel	15-Nov-1994	Ventilation Trials
Tower	0.13	MPV	Driver	Tower Test Tunnel	15-Nov-1994	Ventilation Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	06-Feb-1995	Decoking Trials
Tower	0.30	MPV	Nil Personnel	Tower Test Tunnel	06-Feb-1995	Decoking Trials
Tower	0.22	MPV	Nil Personnel	Tower Test Tunnel	06-Feb-1995	Decoking Trials
Tower	0.20	MPV	Driver	Tower Test Tunnel	06-Feb-1995	Decoking Trials
Tower	0.15	MPV	Nil Personnel	Tower Test Tunnel	10-Feb-1995	Decoking Trials
Tower	0.33	MPV	Nil Personnel	Tower Test Tunnel	10-Feb-1995	Decoking Trials
Tower	0.26	MPV	Nil Personnel	Tower Test Tunnel	10-Feb-1995	Decoking Trials
Tower	0.21	MPV	Driver	Tower Test Tunnel	10-Feb-1995	Decoking Trials
Tower	0.07	MPV	Nil Personnel	Tower Test Tunnel	11-Feb-1995	Ventilation Trials
Tower	0.26	MPV	Driver	Tower Test Tunnel	11-Feb-1995	Ventilation Trials
Tower	0.02	MPV	Nil Personnel	Tower Test Tunnel	15-Feb-1995	Ventilation Trials
Tower	0.15	MPV	Driver	Tower Test Tunnel	15-Feb-1995	Ventilation Trials

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.11	MPV	Driver	Tower Test Tunnel	16-Feb-1995	Ventilation Trials
Tower	0.04	MPV	Nil Personnel	Tower Test Tunnel	16-Feb-1995	Ventilation Trials
Tower	0.05	MPV	Nil Personnel	Tower Test Tunnel	20-Feb-1995	Ventilation Trials
Tower	0.12	MPV	Driver	Tower Test Tunnel	20-Feb-1995	Ventilation Trials
Tower	0.10	MPV	Driver	Tower Test Tunnel	24-Feb-1995	Ventilation Trials
Tower	0.04	MPV	Nil Personnel	Tower Test Tunnel	24-Feb-1995	Ventilation Trials
Tower	0.16	MPV	Driver	Tower Test Tunnel	27-Feb-1995	Ventilation Trials
Tower	0.04	MPV	Nil Personnel	Tower Test Tunnel	27-Feb-1995	Ventilation Trials
Tower	0.27	MPV	Driver	Tower Test Tunnel	07-Jun-1995	Decoking Trials
Tower	0.22	MPV	Nil Personnel	Tower Test Tunnel	15-Aug-1995	Decoking Trials
Tower	0.32	MPV	Driver	Tower Test Tunnel	15-Aug-1995	Decoking Trials
Tower	0.35	MPV	Nil Personnel	Tower Test Tunnel	15-Aug-1995	Decoking Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	15-Aug-1995	Decoking Trials
Tower	0.22	MPV	Nil Personnel	Tower Test Tunnel	16-Aug-1995	Decoking Trials
Tower	0.13	MPV	Nil Personnel	Tower Test Tunnel	16-Aug-1995	Decoking Trials
Tower	0.33	MPV	Nil Personnel	Tower Test Tunnel	16-Aug-1995	Decoking Trials
Tower	0.23	MPV	Driver	Tower Test Tunnel	16-Aug-1995	Decoking Trials
Tower	0.30	MPV	Nil Personnel	Tower Test Tunnel	17-Aug-1995	Decoking Trials
Tower	0.06	MPV	Nil Personnel	Tower Test Tunnel	17-Aug-1995	Decoking Trials
Tower	0.20	MPV	Nil Personnel	Tower Test Tunnel	17-Aug-1995	Decoking Trials
Tower	0.19	MPV	Driver	Tower Test Tunnel	17-Aug-1995	Decoking Trials
Tower	0.28	MPV	Driver	Tower Test Tunnel	21-Aug-1995	Decoking Trials
Tower	0.21	MPV	Nil Personnel	Tower Test Tunnel	21-Aug-1995	Decoking Trials
Tower	0.35	MPV	Nil Personnel	Tower Test Tunnel	21-Aug-1995	Decoking Trials
Tower	0.07	MPV	Nil Personnel	Tower Test Tunnel	21-Aug-1995	Decoking Trials
Tower	0.30	MPV	Nil Personnel	Tower Test Tunnel	20-Jun-1998	Scrubber Tank Trials

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.08	Powertram	Nil Personnel	Tower Test Tunnel	02-Nov-1994	Ventilation Trials
Tower	0.72	Powertram	Nil Personnel	Tower Test Tunnel	02-Nov-1994	Ventilation Trials
Tower	0.03	Powertram	Nil Personnel	Tower Test Tunnel	04-Nov-1994	Ventilation Trials
Tower	0.67	Powertram	Nil Personnel	Tower Test Tunnel	04-Nov-1994	Ventilation Trials
Tower	0.41	Powertram	Nil Personnel	Tower Test Tunnel	07-Nov-1994	Ventilation Trials
Tower	0.02	Powertram	Nil Personnel	Tower Test Tunnel	07-Nov-1994	Ventilation Trials
Tower	0.55	Powertram	Nil Personnel	Tower Test Tunnel	07-Nov-1994	Ventilation Trials
Tower	0.03	Powertram	Nil Personnel	Tower Test Tunnel	07-Nov-1994	Ventilation Trials
Tower	0.02	Powertram	Nil Personnel	Tower Test Tunnel	08-Nov-1994	Ventilation Trials
Tower	0.37	Powertram	Nil Personnel	Tower Test Tunnel	08-Nov-1994	Ventilation Trials
Tower	0.25	Powertram	Nil Personnel	Tower Test Tunnel	08-Nov-1994	Ventilation Trials
Tower	0.02	Powertram	Nil Personnel	Tower Test Tunnel	08-Nov-1994	Ventilation Trials
Tower	0.25	Powertram	Nil Personnel	Tower Test Tunnel	09-Nov-1994	Ventilation Trials
Tower	0.02	Powertram	Nil Personnel	Tower Test Tunnel	09-Nov-1994	Ventilation Trials
Tower	0.73	Powertram	Nil Personnel	Tower Test Tunnel	11-Feb-1995	Ventilation Trials
Tower	0.72	Powertram	Nil Personnel	Tower Test Tunnel	11-Feb-1995	Ventilation Trials
Tower	0.62	Powertram	Nil Personnel	Tower Test Tunnel	15-Feb-1995	Ventilation Trials
Tower	0.25	Powertram	Nil Personnel	Tower Test Tunnel	15-Feb-1995	Ventilation Trials
Tower	0.46	Powertram	Nil Personnel	Tower Test Tunnel	16-Feb-1995	Ventilation Trials
Tower	0.19	Powertram	Nil Personnel	Tower Test Tunnel	16-Feb-1995	Ventilation Trials
Tower	0.06	Powertram	Nil Personnel	Tower Test Tunnel	20-Feb-1995	Ventilation Trials
Tower	0.24	Powertram	Nil Personnel	Tower Test Tunnel	20-Feb-1995	Ventilation Trials
Tower	0.32	Powertram	Nil Personnel	Tower Test Tunnel	24-Feb-1995	Ventilation Trials
Tower	0.09	Powertram	Nil Personnel	Tower Test Tunnel	24-Feb-1995	Ventilation Trials
Tower	0.23	Powertram	Nil Personnel	Tower Test Tunnel	27-Feb-1995	Ventilation Trials
Tower	0.59	Powertram	Nil Personnel	Tower Test Tunnel	27-Feb-1995	Ventilation Trials

Mine	DP Concentration (mg/m^3)	Machine Type	Job Type	Job Location	Sample Date	Project
Tower	0.30	Powertram	Nil Personnel	Tower Test Tunnel	07-Aug-1997	Exhaust Filters
Tower	0.31	Powertram	Nil Personnel	Tower Test Tunnel	07-Aug-1997	Exhaust Filters
Tower	0.90	Powertram	Nil Personnel	Tower Test Tunnel	08-Aug-1997	Exhaust Filters
Tower	1.07	Powertram	Nil Personnel	Tower Test Tunnel	08-Aug-1997	Exhaust Filters
Tower	0.06	Wagner	Nil Personnel	Tower Test Tunnel	25-Jun-1997	Exhaust Filters
Tower	0.99	Wagner	Nil Personnel	Tower Test Tunnel	25-Jun-1997	Exhaust Filters
Tower	1.05	Wagner	Nil Personnel	Tower Test Tunnel	25-Jun-1997	Exhaust Filters
Tower	0.87	Wagner	Driver	Tower Test Tunnel	25-Jun-1997	Exhaust Filters

APPENDIX 3

GUIDELINE FOR THE EVALUATION AND CONTROL OF DIESEL PARTICULATE IN THE OCCUPATIONAL ENVIRONMENT

PREPARED FOR THE AUSTRALIAN INSTITUTE OF OCCUPATIONAL HYGIENISTS

A GUIDELINE FOR THE EVALUATION AND CONTROL OF DIESEL PARTICULATE IN THE OCCUPATIONAL ENVIRONMENT

PREPARED FOR THE AUSTRALIAN INSTITUTE OF OCCUPATIONAL HYGIENISTS

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TABLE OF CONTENTS

1.0 INTRODUCTION

The invention of the diesel engine by Rudolph Diesel in the 1890's has over the past 115 years contributed significantly to the productivity of many nations. As a result of the widespread use of larger diesel powered equipment, there is increased potential for adverse health outcomes due to the larger number of workers exposed to the complex mixture of toxic gaseous, adsorbed organics and particulate components found in the raw exhaust emissions.

While the adverse health effects of the gaseous fraction of diesel emissions has been known for some time, research conducted over the last two decades indicates that the particulate component of the diesel exhaust will most likely contribute to potential health effects, as well as visual and nuisance pollution. The focus of this document is the carbonaceous component (elemental and organic carbon) of the particulate matter consistent with regulatory trends that have been developing overseas during the last decade.

Early toxicological investigations indicated adverse health outcomes in animals, but the major attention to the issue arose in 1988, when the National Institute for Occupational Safety and Health (NIOSH) in the USA formally suggested a link between occupational exposure to diesel particulate and lung cancer (NIOSH 1988). Since then the issue has become the subject of increasing scientific and public interest. Moreover, in the past few years statutory authorities have begun to impose occupational and environmental limits on the amount of diesel particulate that diesel engines produce, and in some jurisdictions introduce workplace and environmental exposure limits and control strategies.

The purpose of this guideline is to provide readers with an overview of the current status in respect to diesel particulate and to provide guidance on proven monitoring and control technologies for the workplace. Much of the basic investigative work has been reported from overseas studies and considerable refinement and successful application have been made in Australian industry over the last 12 years, and this is presented and referenced in this document. As the underground mining industry has been the focus of much research (due to potentially higher exposures), much of the detail of this document is mining based, however application to other industrial situations should, in most cases, be similar.

2.0 COMPOSITION OF DIESEL PARTICULATE

Although it was recognised at an early stage that the “blue haze” associated with the use of diesel equipment was related to particulate matter (soot), it was not until the mid 1970’s that the composition and characteristics of diesel particulate (DP) were mostly resolved.

Amman and Hillman (1982) summarised the early research on this aspect and defined diesel particulate as “consisting principally of combustion generated carbonaceous soot with which some unburned hydrocarbons have become associated”. Using photomicrographs of the exhaust from a diesel passenger car, he demonstrated that diesel particulate were made up of a collection of basically spherical primary particles termed “spherules” which were agglomerated into aggregates ranging in appearance from resembling a cluster of grapes to resembling a chain of beads. Subsequent researchers have confirmed that the spherules (as nanoparticles) vary in diameter between 10 and 80 nm with most in the 15 - 30 nm range.

Examination of diesel particulate collected in Australian mines clearly demonstrated the spherical nature of the basic particles and their tendency to form "chains" and agglomerations. High resolution electron microscopy indicated that the basic spherule consisted of an irregular stacked graphitic structure, the so called "elemental carbon" (Rogers, Davies and Conaty 1996, WHO 1996).

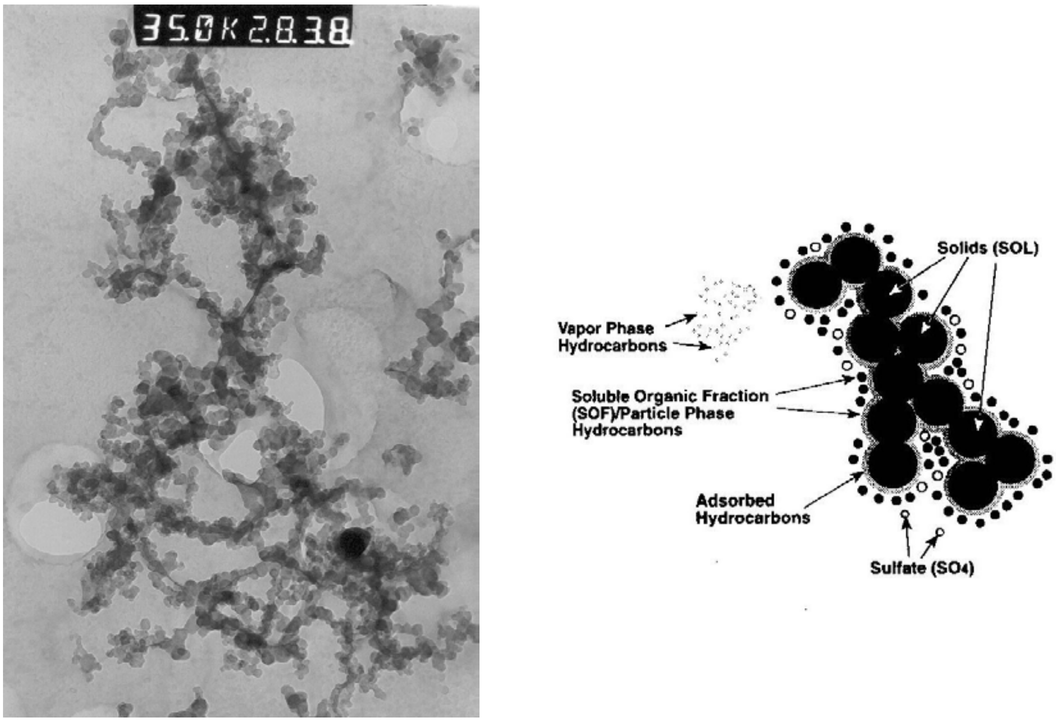

Figure 1 - Electron micrograph and schematic - mine diesel particulate showing spherules, chains and agglomerates
(Source: Rogers 2004)

The graphitic nature and high surface area of these very fine particles (typically <1 μm) means they have the ability to absorb significant quantities of hydrocarbons (the organic carbon fraction) originating from the unburnt fuel, lubricating oils and the compounds formed in complex chemical reaction during the combustion cycle.

The combination of the small particle size, their ability to absorb chemical organic compounds such as polycyclic aromatic hydrocarbons (PAHs) and their potential to penetrate and deposit in the deep sections in the lung was the early basis for concern and research in regard to adverse health effects. However subsequent research suggested an alternate mechanism based mainly on particle overload. Traces of inorganic compounds were also found in the particulates, eg sulphur, zinc, phosphorous, calcium, iron, silicon and chromium. These were attributed to have arisen from the fuel and additives to the lubricating oil used in the engine.

The DP spherules are formed rapidly (in the order of nanoseconds) during the combustion process (Kittelson 2001, HEI 1995, 2002). The rate of formation is dependent on factors such as fuel quality, rate of burn, engine design and the basic mechanism is a chain reaction which appears to be promoted by seed particles such as sulphates and other nanoparticles. A basic understanding of the mechanism of DP formation has assisted in the design of control mechanisms (eg low sulphur fuels reduce the formation of sulphate and the subsequent reduced seeding of particle formation) and systems for capture and measurement of DP.

In summary, diesel particulate have the following characteristics.

- Consist primarily of small particles (15 – 30 nm) called spherules, which quickly agglomerate to form chains and larger particles, which are typically less than 1 μm in diameter.
- The spherules are rapidly formed in the combustion process.
- Have the ability to absorb significant quantities of hydrocarbons and other organic compounds (organic carbon fraction).
- Contain traces of inorganic compounds (eg sulphate, nitrate, metals and other trace elements).

- Are in the size range where they are readily transported and deposited deep in the human respiratory system.

3.0 HEALTH EFFECTS

The potential for adverse health effects arising from occupational exposure to diesel particulate has been the subject of intense scientific debate for the past 25 years.

3.1 Non-malignant Effects

Raw diesel exhaust contains a complex mixture of toxic gases and particulate matter that has the potential to irritate the mucus membranes of the eyes and respiratory system. Traditionally this irritant effect has been attributed to aldehydes in the exhaust gases, however extensive field testing for aldehydes and formaldehyde has failed to link the two factors. The major factor for irritation arises from the fine diesel particulate which impact with the mucus membranes causing a local irritant effect and at high concentrations a stinging sensation and lachrymation.

***Animal Studies*:** A review of 50 reported animal studies involving long term exposures to high concentrations of diesel particulate (eg 70-80 mg/m^3, which is some 10-50 times higher than values which have been observed to cause respiratory tract irritation in the underground mining industry) indicates that such extreme exposures can result in non-cancerous pulmonary effects. The effects include chronic inflammation, epithelial cell proliferation and depressed alveolar clearance, metaplasia, alterations in connective tissue, pulmonary fibrosis and compromised pulmonary function, showing a restrictive and obstructive pattern. The presence of these effects, introduced at such high exposures, does not dramatically compromise the survival time of chronically exposed animals. Below these high reported dose levels, an effect of diesel exhaust exposure is not detectable (HEI, 1995).

Human Epidemiological Studies: The Health Effects Institute also reviewed six short term exposure studies, nine long term exposure studies and nine mortality studies of various groups of workers exposed to diesel exhaust (HEI, 1995). It concluded:

Short-Term Exposures: Six studies (on iron ore miners, salt miners, coal miners, bus garage workers, stevedores) measured the effects of exposure to diesel exhaust on changes in pulmonary function during a single work shift. All but one found little evidence of changes in pulmonary function related to diesel exhaust exposure. It was not clear to what extent acute responses from exposure may indicate an increased risk of chronic respiratory disease.

Long-Term Exposure: Nine studies have been conducted on railroad workers, iron ore miners, potash miners, coal miners, salt miners, bus garage workers and stevedores. Although six of the studies were based on various miners, they did not provide strong or consistent evidence for chronic, non-malignant respiratory effects associated with occupational exposure to diesel exhausts.

Mortality Studies: A review of nine cohort studies (on railroad workers, bus garage maintenance workers, heavy equipment operators, sulphide ore miners, bus drivers) did not provide consistent evidence of an effect of occupational exposure on mortality from non-malignant respiratory disease. Subsequent meta analysis studies have not clarified the situation as these studies have themselves been the subject of controversy within the scientific community.

3.2 Malignant (cancer) Effects

Animal Studies: One of the first reports of the carcinogenic potential of diesel emissions was by Kotin, Falk and Thomas (1955) who demonstrated that skin papillomas and cancers developed when acetone extracts of the particulate matter found in diesel engine emissions were painted onto the skin of mice.

These findings did not receive much attention and it was not until Ames, McCann and Yasmasaki (1975) introduced a short-term bacterial mutagenicity assay (which was adopted by some regulatory authorities as a tool to predict carcinogenicity) that further evidence was reported. Several researchers (Huisingh et al 1978, Wang et al 1978) reported that organic solvent extracts of diesel exhaust particulate matter produced mutations in bacteria.

Studies in the 1980’s focused on identifying the potentially hazardous constituents of diesel particulate. This research identified hundreds of chemicals of which PAHs received particular attention due to their potent mutagenic and carcinogenic potential (IARC 1989). Westerway (1982) measured PAH levels in five underground mines in Canada and found higher than ambient concentrations, albeit less than that found in large cities. Westerway demonstrated that PAH concentrations were affected by factors such as distance from the diesel, type of ore mined, size of the mine drift, type of explosive used, the design of the mine, the type of catalytic converter used, the fuel used and possibly the type of diesel engine used. Later Bagley et al (1992) reported PAH levels and assays on airborne samples collected in US coal mines.

Consequently, research as to the health effects of diesel particulate was guided through the 1980’s on the basis that they were a carcinogenic hazard because they contained potential mutagens and carcinogens adsorbed onto the surfaces of particles. These particles were in a size range that allowed them to be inhaled into the deep regions of the lungs, thus allowing the adsorbed chemicals to be taken up by the body, interact with DNA and initiate carcinogenesis. Concern as to the bioavailability of these chemicals dominated toxicological research at the time.

During the 1980’s a number of animal bioassays were conducted by groups in the USA, Europe and Japan.

The findings of all these groups were consistent and suggested that if diesel exhaust was inhaled at high concentrations for periods in excess of 24 months, lung tumours were prevalent in rats. Little account was taken in these studies of potential lung overload effects. Some studies compared raw exhaust to filtered exhaust and only found tumorigenic effect from the raw vapour phase thus implicating the particulate phase.

These findings prompted two research groups to investigate the contribution of particles in diesel exhaust in the development of tumours in rats. Mauderly (1992) and Heinrich et al (1995) both reported that when inhaled at high concentrations for prolonged periods both diesel particulate and chemically inert carbon black (no adsorbed chemicals present) induced tumours in rats. These findings suggested that the adsorbed carcinogens on the diesel particulate were not the cause of tumours in rats as had been previously hypothesised and that the particulate itself might play a more dominant role in the carcinogenic pathway. The process appears to involve particle overload at very high concentrations as no carcinogenic effect is observed at lower particle concentrations. Some researchers (HEI 1995, Mermelstein et al 1994) consider that the overload mechanism observed in rats may not be applicable to humans, who are generally exposed to much lower concentrations that produce no particle overload of the lung.

Nevertheless, the work of Mauderly (1992) has focused attention on the physical nature of particles themselves as a potential carcinogen, with a resultant upsurge in research on the core particle component, elemental carbon.

A recent shift in the debate on the mechanism for potential adverse health effects has occurred from studies in the environmental arena. This has centred on the role of ultrafine and nanoparticles generated from newer diesel engines as against older designs.

The presence of greater levels of ultrafine particles in the exhaust of newer diesel engines has been considered by some researchers to be a factor in the development of adverse health effects such as cancer. The supporting evidence is very limited and its interpretation the subject of ongoing scientific debate.

This debate is best summarised by Kittelson (2001) who highlights the fact that unlike carbonaceous soot particles associated with older diesel engines, these ultrafine particles are formed by gas to particle conversion processes from vapour phase particle precursors as the exhaust of newer design engines dilutes and cools in the atmosphere. Kittelson's work shows that nanoparticle measurements may be effected by artefact formation and the results are very strongly influenced by the sampling and dilution techniques employed.

Epidemiological Studies There have now been at least 34 published epidemiological studies that analyse the health outcomes or lack of outcome from exposure to diesel particulate. More than half of the studies have produced negative outcomes in that they do not find an elevated risk of lung cancer in groups exposed to diesel exhaust emissions. For the positive studies most have been carried out in a manner inconsistent with normal epidemiological practices and lack information on major confounders for lung cancer such as tobacco smoking, asbestos exposure and relative degree of potential exposure to diesel exhaust. None of these 34 studies are supported with actual exposure data relevant to the cohorts.

The first epidemiological study to examine the relationship between lung cancer and occupational exposure to diesel exhaust was conduction on the workforce of London Transport (Raffle 1957).

The findings were opposite to that expected, with Engineering staff in the bus garages who had the highest exposures to diesel engine exhaust showing no excess of lung cancer (0.75), whilst the trolleybus engineering staff which had the second lowest exposures, produced a slightly elevated lung cancer risk (1.12). The group was studied and reported on for a further 20 years with no increased risk of lung cancer detected.

Other studies in the transportation industry (rail workers, bus/garage workers) provide contrary results. The two key epidemiological studies commonly quoted in this area are those of Garshick et al (1988) (rail workers) and Steenland, Silverman and Zaebst (1992) (truck drivers). Garshick et al (1988) found a significantly increased odds ratio for lung cancer of 1.4 (1.06 – 1.88, 95% CI) and Steenland, Silverman and Zaebst (1992) found an increased risk of lung cancer of 1.3 (0.81 – 2.21, 95% CI).

A critical review of these two studies, has determined that they have different validities. (HEI 1995)

In respect to the US railway workers study (Garshick et al 1987, 1988), the HEI found an increased lung cancer risk in groups such as train workers, shop workers and clerks, however these risks were not found to be dose related. In fact, the risk decreased as duration of exposure (and hence increasing cumulative exposure) increased (Crump, Lambert and Chen 1991). HEI suggested that since the dose response was negative in all three occupational categories, some form of bias is present in the data. They went on to suggest that this bias may have resulted from uncontrolled confounding by cigarette smoking, by other occupational exposure agents, misclassification of occupational groups or other factors.

In regard to the truck drivers study (Steenland, Silverman and Zaebst 1992), HEI concluded that the study had a weakness in that it used estimates to reconstruct past exposures. Concern was expressed that these estimates most likely under-estimated exposures in the early years as they were based on general trends in truck usage, fuel and emission rates.

Overall, HEI concluded that, based on the identifiable deficiencies in these two studies, that either individually or in combination, they did not provide adequate data for quantitative risk analysis. Recommendations were made for the development of additional studies designed to resolve the epidemiological issue.

While underground miners represent a relatively high exposure group to diesel particulate (Haney 1992) they generally have not been targeted for epidemiologic studies due to their small population size and the confounding exposure to other contaminants (eg dusts).

Two reviews (NIOSH 1995, IARC 1997) indicate that most studies show that coal miners have a lower than expected risk of developing lung cancer. No information was available to determine the extent, or effect if any, of exposure to diesel particulate in these studies.

A large scale investigation into cancer risk in the NSW coal industry was completed in 1994 and updated in 1997. This involved matching the employment medical records with the records of the NSW Central Cancer Registry of 23,630 men who entered the industry at or after 1973 up until the end of 1992. The overall standardised cancer incident ratio was lower than the general population (0.82 95% CI 0.73-0.92). For lung cancer the rate was much less than the normal (SIR 0.74 95% CI 0.50-1.06) (Christie 1994, Brown et al 1997). Although it is certain that all underground workers in the cohort had at some stage been exposed to diesel particulate, it is not possible to determine what influence exposure to diesel particulate or other factors had on the study outcomes.

A project with relevance to the mining industry is that being undertaken by Dahman (2003) in Germany. Here a longitudinal epidemiological study is being undertaken at two underground salt/potash mines with the focus being on lung issues. To date no results have been published.

A diversity of interpretations has been made by various authors in reviewing these epidemiological studies. The interpretation appears to depend on how the negative studies and statistical uncertainties are treated.

After reviewing 30 epidemiological studies of workers exposed to diesel emissions in occupational settings for the period 1950 to 1980 HEI (1995) concluded that:

> *"The epidemiologic data are consistent in showing weak associations between exposure to diesel exhaust and lung cancer. The available evidence suggests that long-term exposure to diesel exhaust in a variety of occupational circumstances is associated with a 1.2 to 1.5-fold increase in the relative risk of lung cancer compared with workers classified as unexposed."*

The HEI did sound a note of caution due to the lack of definitive exposure data and an inability to determine the influence of confounding factors.

A significant number of epidemiologic studies of diesel exhaust have been criticised due to the failure by researchers to correct for confounding factors (eg smoking, other contaminants) and to the complete lack of diesel particulate exposure data from the period when the workers being evaluated were exposed. Given these factors, two research groups, Bhatia, Lepipero and Smith (1998) and Lipsett and Campleman (1999) set out to conduct a comprehensive statistical "meta-analysis" of the epidemiologic literature.

The meta-analysis process aims to systematically combine the results of previous studies in order to generate a quantitative summary of a particular body of research and to examine the influence of sources of variability among studies. In both cases Bhatia, Lepipero and Smith (1998) and Lipsett and Campleman (1999) concluded that the meta-analysis supported a causal association between increased risk of lung cancer and exposure to diesel exhaust.

Stober and Abel (1996), in reviewing the meta analysis approaches, commented that most previous reviews and meta analysis studies have excluded the negative outcome studies.

Stober reviewed the negative studies and used it as supporting evidence that there is no detectable lung cancer risk outcome. Based on the absence of smoking habits in almost all of the cohorts, and lack of exposure estimates, Stober and Abel (1996) concluded that after decades of study no real data existed to conclude from epidemiological studies that exposure to diesel emissions results in increased risk of lung cancer.

Cox (1997) examined the discrepancies in the epidemiological studies that lead to differing interpretation of the risk outcomes. His analysis was based on statistical associations that are found in some studies and the lack of overall causal association. He developed an epidemiological risk assessment model using techniques from artificial intelligence and statistical steps to clarify the causal interpretation of complex multivariate data sets. When this was applied to the key study of Garshick et al (1988), the results indicate that the diesel emission concentration has no positive causal association with occupational lung cancer risk.

Reviews by Morgan and Dainty (1997), have taken a broader approach including the detailed examination of the negative studies. They have concluded that the weight of evidence is against the hypothesis that diesel particulate results in lung cancer in humans.

It is possible to conclude that the epidemiological studies that have been published over the last 20 years fail to consistently and logically establish that a consistent and significant lung cancer risk exists across those industries where there is significant exposure to diesel particulate.

Notwithstanding these studies, evidence suggests that a potential significant initiation effect exists within work groups exposed to high levels of diesel particulate and/or diesel emissions.

In many cases regulatory authorities in the USA, Europe and Canada have concluded that sufficient evidence exists to indicate that diesel particulate does present an increased risk of lung cancer, however in many instances the quantification of potency has been, and continues to be, an area of intense debate. Given this situation of scientific uncertainty, many organisations have adopted a policy of caution and support the minimisation of employee exposure wherever possible.

Adoption of this strategy within the Australian underground coal mining industry has reduced employee irritant effects and increased productivity, however the issue of whether this results in a reduced lung cancer outcome remains unresolved.

Within the underground mining industry both MSHA (2001) and the New South Wales Joint Coal Board (1999) have indicated that they consider diesel particulate to be a potential carcinogen. The Joint Coal Board's Chief Medical Officer stated "Diesel particulate may be cancer-causing, possibly at the risk level of passive cigarette smoking exposure" (Joint Coal Board 1999).

In May 2002 the United States Environmental Protection Agency published their health assessment for diesel engine exhaust (US EPA 2002).

The stated aim of the document was to identify and characterise the potential human health hazards of diesel exhaust and to estimate the relationship between exposure and disease response. It concluded that diesel particulate matter was the most appropriate parameter of total diesel exhaust to correlate with human health effects until more definitive information about the mechanisms of toxicity or mode of action become available.

In regard to health effects the US EPA based their conclusions on diesel engines built prior to the mid 1990's and suggested they fell into three categories. These were:

- Acute Effects
  Eye, throat and bronchial irritation, light headedness, nausea, cough and phlegm.

- Chronic Non-cancer Respiratory Effects
  Based on animal evidence the potential existed for chronic respiratory disease.

- Chronic Carcinogenic Effects
  Lung cancer was evident in occupationally exposed groups and was thought to be a hazard at lower environmental exposures.

The US EPA also sounds a warning by pointing out the many uncertainties that exist due to assumptions being used to bridge data and knowledge gaps.

As well as lung cancer, some epidemiological studies have suggested that an elevated risk of bladder cancer may be linked to diesel exhaust exposure in occupational environments. The evidence for bladder cancers is however not as extensive or definitive as that for lung cancer.

4.0 WORKPLACE EXPOSURE STANDARDS

The development of a workplace exposure standard for diesel particulate is still in a state of flux. This is as a result of the paucity of dose response risk data, different approaches to sample collection and analysis methodology, and different approaches being taken by various industry segments advisory groups and regulatory authorities

Even though there are a number of exposure values currently in use, direct comparisons cannot necessarily be made as the basis for each value differs depending on reliance on measurement of respirable versus sub micron fraction, and subsequent analysis of gravimetric versus specific carbon species (for specifics refer section 5.0).

Diesel particulate is created in a dynamic and variable process and hence the proportion of the various specific fractions can exhibit a wide range of proportions. However, for comparison purposes the following approximations have been determined in a number of studies:

- Diesel Particulate is a sub set of the respirable dust fraction.
- Almost all (> 90%) of the diesel particulate (DP) is in the sub (<1) micron size fraction.
- Some DP methodologies sample the respirable fraction and others sample the sub-micron fraction of the work environment. Both respirable and submicron sampling capture DP. Other aerosols can give rise to errors in measurement unless analytical methods specific to diesel particulate are used.
- The aerosol fraction (respirable or submicron) collected to represent diesel particulate matter (DPM) consists of diesel particulate plus also a fraction of other types of aerosols present in the work environment.

DPM fraction ≡ Diesel particulate + Mineral Fraction + other aerosols (oil, tobacco smoke etc)

Diesel particulate ≡ carbon core (elemental carbon) + adsorbed organics (organic carbon)

Elemental Carbon + Organic Carbon ≡ Total Carbon

Submicron Total Carbon ≡ 80% Diesel Particulate

Submicron Elemental Carbon ≡ 50% Diesel Particulate

4.1 International Regulatory Standards

Canada and Germany were the first countries to introduce statutory exposure limits for diesel particulate in underground mines.

These limits were reported as 1.5 mg/m^3 in Canadian non-coal mines (Watts 1992) and 0.6 mg/m^3 for German non-coal mines (Dahman 1997).

The level of exposure standards in Canadian mines however has changed over the years, with most Canadian provinces having a respirable combustible dust standard (RCD) of 1.5 mg/m^3. This is expected to change in 2003 with Quebec moving to 0.6 mg/m^3 (RCD) and Ontario 0.4 – 0.6 mg/m^3 (RCD). These values appear to have been set based on the lower limit of detection of the RCD method rather than on a dose response relationship.

The German mining industry has also had a long association with regulatory authorities in the development of exposure standards. Their approach has been to develop a technical rule for toxic substances (or TRGS) rather than a dose response exposure standard. In underground non-coal mining and construction activities this is set at 0.3 mg/m^3 elemental carbon.

In regard to coal mines the potential level of particulates in every production site is calculated from vehicle emission and ventilation rates (Dahman 2003). If the value of 0.3 mg/m^3 elemental carbon is exceeded, steps are taken to either reduce the number of machines or increase ventilation levels.

The most activity in respect to recent exposure standards has occurred within the US mining industry.

In 1998 the US Mine Safety and Health Administration (MSHA) proposed an exposure standard of 0.16 mg/m^3 submicron total carbon for metallic underground mines, and suggested that this was equivalent to 0.2 mg/m^3 submicron whole diesel particulate matter (MSHA 1998). No toxicological or risk analysis was provided to support the value. It is interesting to note that coal mines have been excluded from these proposed standards due to the perceived difficulties in analysis (ie carbon from diesel particulate in the presence of carbon from coal).

Research in Australian coal mines indicates that such interference is negligible provided correct sampling and analytical procedures are adopted. (Rogers and Whelan 1996).

To overcome this perceived exposure measurement problem in coal mines, MSHA promulgated an alternate raw exhaust particulate emission standard of 2.5 g/hr (MSHA 2001). This standard is only applied at the engine approval stage and is not measured in routine service but used as a guide by operators to develop effective control strategies.

As the result of legal action a negotiated agreement has been reached with MSHA (2002) in regard to workplace exposure standards in metal and non-metal mines.

The agreed standard is 0.4 mg/m^3 submicron total carbon for an interim period, concluding on 20 January 2006, when the standard reverts to the 1998 proposal of 0.16 mg/m^3 submicron total carbon. A collaborative study was undertaken in 31 mines to evaluate the practicality of the proposed sampling and analysis method.

In August 2003 (Federal Register 2003) MSHA issued a notice indicating that the final permissible exposure limit for underground metal and non-metal mines would be based on elemental carbon rather than the previously proposed total carbon. This change in direction appears to be linked to interferences observed in the 31 mine study where drill oil mist and environmental tobacco smoke in personal samples added to the overall total carbon content. Based on a stance that elemental carbon makes up 77% of total carbon content of diesel particulate, the current (to 2006) exposure standard is 0.308 mg/m^3 submicron elemental carbon and future (post 2006) exposure standard is 0.123 mg/m^3 submicron elemental carbon. To determine compliance a further error factor of 1.12 and 1.15 is applied to the respective exposure standards.

4.2 ACGIH Recommendations

In regard to general workplace exposures, the American Conference of Governmental Industrial Hygienists (ACGIH) between 1995 and 2002, has proposed a number of draft recommended standards ranging from 0.05 – 0.15 mg/m^3 diesel particulate with no clear rationale as to the monitoring technique.

A review of this standard since its first listing on the notice of intended changes provides some insight into the state of flux currently surrounding the promulgation of a universal workplace exposure standard (Table 1).

Table 1

1995	0.15 mg/m^3 (< 1µm)	A2 (suspected human carcinogen)
1999	0.05 mg/m^3 (< 1µm)	A2
2000	0.05 mg/m^3 (< 1µm)	A2
2001	0.05 mg/m^3 (respirable)	A2 (measured as elemental carbon)
2002	0.02 mg/m^3	A2
2003	-	Withdrawn from list of intended changes

This last published draft standard (ACGIH 2002) proposed a value of 0.02 mg/m^3 (elemental carbon) and suggests that total carbon is approximately equal to 85% of diesel particulate matter and 30 – 70% for elemental carbon (ACGIH 2000). In 2003 this value was removed, without explanation, from the list of intended changes (ACGIH 2003).

The withdrawal of the ACGIH proposal, has affected some European countries (e.g. Switzerland, Austria) as they have followed the trends in the ACGIH approach in order to control employee exposures in tunnelling projects. The direction of exposure setting within Europe at this stage remains unclear.

4.3 Australian Exposure Standards

Currently there appears to be no legislative exposure standard for diesel particulate in Australia.

Historically, on the basis of best available evidence and recommendations listed from Canadian studies, a value of 2 mg/m^3 “organic particulates” (internal respirable combustible dust analysis method) was adopted for use from the late 1980’s and then later as a standard in NSW metalliferous mines (NSW Department of Minerals and Energy 1989, NSW Department of Mineral Resources 1996). This exposure standard has been removed in the most recent publication of Guidelines for Safe Mining, a NSW supplement to the National Safe Mining Handbook.

Research within the Australian mining industry has found that if atmospheric levels of diesel particulate are reduced below 0.2 mg/m^3 (DP) or approximately 0.1 mg/m^3 elemental carbon, the level of eye and upper respiratory tract irritation is significantly reduced. This outcome has evolved from observations made over a number of years whilst collecting in excess of 1,000 personal samples across a wide range of mines and mining operations (Pratt et al 1997, Rogers and Davies 2001). On this basis the NSW Minerals Council (1999) has proposed an industry best practice exposure standard of 0.2 mg/m^3 (as submicron DP, equivalent to 0.16 mg/m^3 submicron total carbon, or 0.1 mg/m^3 submicron elemental carbon). The Minerals Council acknowledges that although compliance with such a standard would offer substantial improvement for workers comfort, there is insufficient evidence to suggest such a standard would prevent the development of diseases such as cancer. The Minerals Council publication goes on to suggest that worker exposure levels to diesel particulate should be reduced as low as reasonably practicable through effective control strategies.

In summary, the promulgation of a dose response workplace exposure standard linked to sound epidemiological or dose response evidence does not appear likely within the near future. There is strong evidence to indicate that reducing workplace exposures to below 0.2 mg/m^3 submicron DP (or 0.1 mg/m^3 submicron elemental carbon) will significantly reduce irritation effects. In situations where this standard has been introduced and achieved, the number of employee complaints has dropped (or in many cases ceased) and productivity gains have been observed.

The effectiveness of such a standard in reducing the potential risk of cancer is as yet unknown, due to the uncertainties surrounding published epidemiological studies.

5.0 WORKPLACE MONITORING AND ANALYSIS METHODS

Research has been underway for a substantial period to establish reliable methods of estimating worker exposures. Initial approaches to monitoring diesel particulate followed that which had historically been used to monitor respirable dust. Up until the early 1970's the contribution of combustible material "soot" had been recognised as being a significant proportion of the respirable dust fraction but limited action was taken to quantify this fraction. This arose essentially due to the limited knowledge at that time in regard to the formation, composition and size distribution of diesel particulate and the availability of suitable specific methods for determining diesel particulate in the presence of other workplace aerosols.

5.1 Respirable Combustible Dust (RCD)

In 1971 a major metalliferous mining company in Canada participated in a research project to measure the combustible fraction of the respirable portion of airborne dust (Stachulak and Conrad 1998). The method was optimised over several years and resulted in the monitoring technique "Respirable Combustible Dust" or RCD.

The technique involves the collection of respirable dust on a silver membrane using the standard miniature cyclone. The filter is weighed prior to heating in a muffle furnace for one hour at 400°C. The filter is re-weighed with the amount of material being lost deemed RCD. This method has found substantial support, especially in the Canadian metalliferous mining industry, however its application to coal mines has not been possible due to its dependence on the combustion of material of which a major proportion would be coal dust. Its application in other industries has been restricted essentially due to interference from other sources of organic material and its relatively high practical detection limit of around 0.5 mg/m^3.

A similar approach to measuring the soot in respirable dust samples was taken in surveys conducted at the metalliferous mines at Broken Hill from 1982. The respirable dust samples were collected on glass fibre filters and the carbon content measured by weight loss after pyrolysis in a low temperature plasma asher.

5.2 Sub Micron Size Selective Sampling

To reduce severe interferences when diesel particulate monitoring in coal mines, McCawley and Cocalis (1986) proposed that existing respirable dust monitoring devices be modified to include a singe-stage impaction pre-separator to collect diesel particulate which had previously been demonstrated to be less than 1 μm (Amman and Siegla1982). This concept was fully investigated by Cantrell and Rubow (1991 & 1992) who demonstrated that a bimodal distribution of aerosol average mass size occurred in mines using diesel equipment (Figure 2).

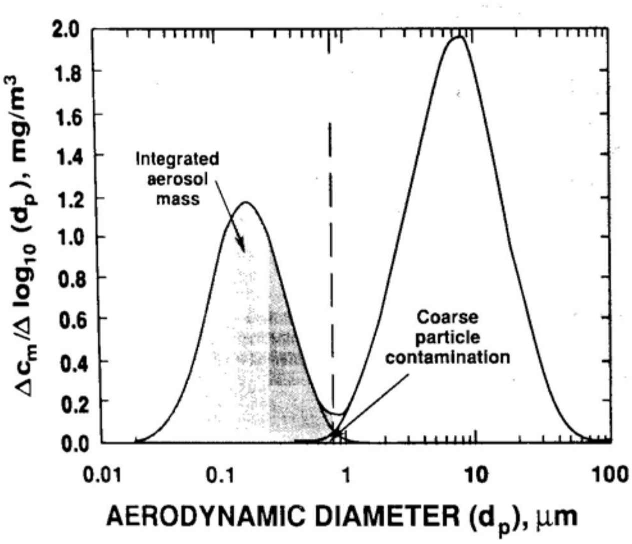

Figure 2 - Size Distribution of Mine Aerosol
(Source: US Bureau of Mines IC 9324)

At approximately 0.8 μm the cut point between the two size fractions (diesel particulate versus general mine dust) is relatively sharp and hence both fractions could be readily separated.

Using this criteria Cantrell and Rubow (1991) proceeded to develop a "Personal Diesel Aerosol Sampler" that consisted of a normal respirable dust cyclone followed by a second stage multiple nozzle impactor with a cut size that only passes aerosol with less than 0.8 μm aerodynamic diameter. The larger than 0.8 μm aerosol was impacted on a greased plate and the less than 0.8 μm aerosol was collected on an open mesh Teflon filter and determined gravimetrically. The sampler operated at 2 litres per minute (L/min) and was designed to be compatible with commercial personal sampling pumps used in the mining industry.

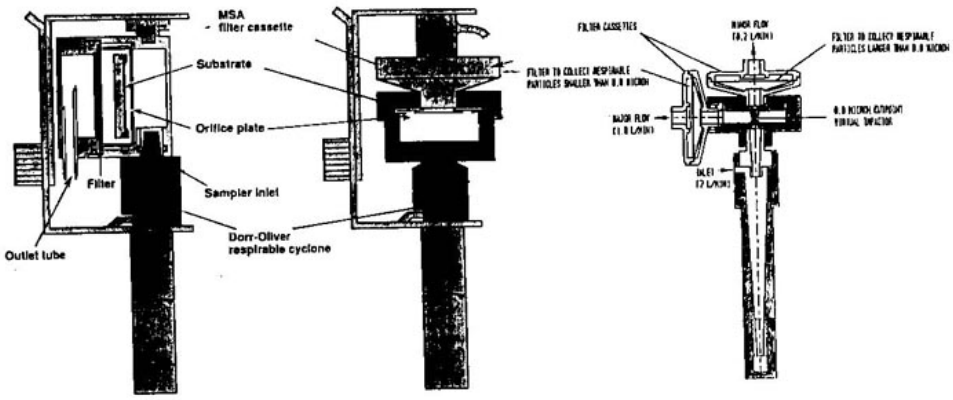

Figure 3 - Sub micron Diesel Particulate Samplers {left to right: Cantrell and Rubow (1991), McCartney and Cantrell (1992), Marple, Rubow and Olsen (1996)}

This sampling instrument has been used from the early 1990's in both the USA and Australia and has been found to be very effective where workplace exposures provided sufficient deposit for accurate gravimetric analysis. Rogers, Davies and Conaty (1993) demonstrated, using analytical electron microscopy, that there was less than 10% positive interference due to non-diesel particulate in coal mines and less than 5% positive interference matter in metalliferous mines providing that the respirable dust levels were kept below about 3 mg/m^3 and 5mg/m^3 respectively.

Whilst the original sub micron diesel particulate sampler did its job well, it was difficult to load, was subject to contamination error and was bulkier and heavier than standard respirable dust sampling heads, hence worker acceptance for personal monitoring was poor.

More user-friendly double cassette systems (one with an oiled plate impaction separator, and one with a collection filter) fitted to a cyclone were developed and were used extensively in occupational hygiene surveys in the USA with a limited trial system being undertaken in Australia (Tomb et al 1990, McCartney and Cantrell 1992, MERIWA, 1998).

The concept was further extended to a personal virtual impaction sampler (MSP Model 230 Diesel particulate Sampler) that used nozzles to split the respirable sampler flow into submicron and respirable submicron fractions. This allowed simultaneous collection of both fractions onto separate filter cassettes and hence a comparison between the amount of components in the submicron versus that in the respirable fraction (Marple *et al* 1995, 1996). Using a controlled split flow system developed in Australia, the sampler could be operated using a single personal sampling pump providing it was well maintained and hence capable of drawing 2 L/min over the working shift against a backpressure of 22" WG (Rogers and Whelan 1996, Rogers and Davies 2001).

Recently, a commercial single-use DP cassette incorporating precision sapphire nozzles, an oiled impactor, and a quartz fibre filter has been developed to meet the sampling requirements listed by MSHA for the US hard rock mining industry (SKC DPM cassette w/impactor 225-317). This cassette was originally designed to fit on top of the outlet of the US Dorr Oliver Cyclone, however this cyclone is not commonly used in Australia. Adaptors were designed and tested by Alan Rogers OH&S Pty Ltd that allow the cassettes to be readily fitted to the style of respirable dust cyclones used in Australia for compliance with AS 2985-1987.

The result is a light-weight sampling device, which is only slightly longer than the normal respirable dust cyclone and hence has gained reasonable worker acceptance when used for personal monitoring. These adaptors are now commercially available (Air-Met 2003).

It should be noted that the quartz fibre filter in these cassettes is that required for analysis of carbon species as per NIOSH 5040, but it is not suitable for gravimetric determinations due to problems with its fragility and localised electrostatic charge. In almost all industrial situations it is necessary to have a cyclone pre-separation phase to prevent dust blocking the impaction holes. In situations where there is high dust concentrations or even high instantaneous dust concentrations, overloading of the separation process occurs and there is particle bounce on the plate impactor, with subsequent overestimation of exposure conditions.

Figure 4 - SKC DPM cassette with impactor 225-317
(Source: Air-Met Scientific Pty Ltd)

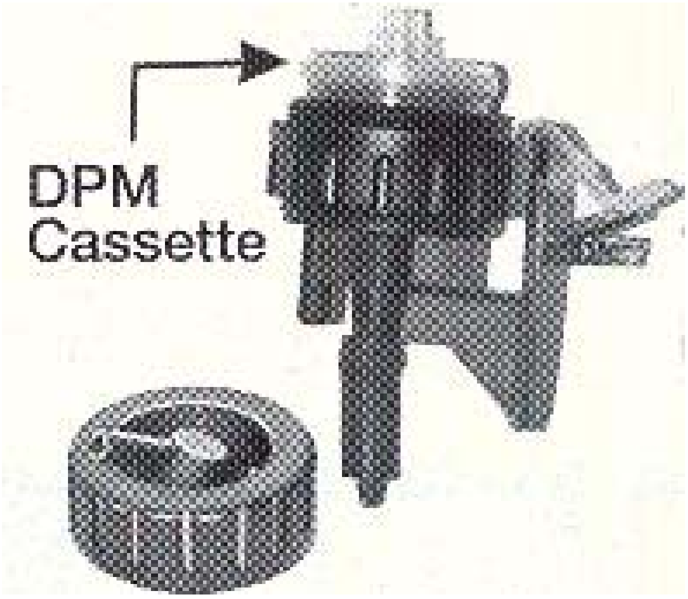

Figure 5 - SKC Respirable Dust Cyclone with modifications to accept SKC DPM cassette *(Source: Air-Met Scientific Pty Ltd)*

5.3 Airborne Sample Analysis

5.3.1 Gravimetric Analysis

Much of the early investigations until the mid 1990's involved simple gravimetric analysis of the respirable fraction (RCD) or the sub micron fraction. The method requires accurate measurement of small increases in mass and hence a considerable step up in precision, handling and weighing techniques way beyond the strict requirements already listed in AS 2985-1987. Filter selection is critical due to the need to balance the effects of weight stability versus low pressure drop for use in the impactors. Teflon® mesh filters are the only substrate that meets the requirements. The pressure drop for PVC and PVC copolymers is too high, while glass fibre and quartz fibre filters are fragile with subsequent mass loss and idiosyncratic characteristics of moisture pick up and localised electrostatic areas.

Results for DP (submicron mass) are reported to the nearest 0.01 mg/m^3 based on the accuracy limit at the 90% confidence level of the microbalance, being about +/-0.01 mg/m^3 for an 8-hour sample and +/-0.02 mg/m^3 for a 4-hour sample. This is lower than the limit of reporting (0.1 mg/m^3) required for Australian regulatory respirable dust sampling, but the value can be achieved with Teflon® filters given sufficient attention to weighing and handling procedures.

5.3.2 Carbon Speciation

The toxicological work of Mauderly (1992) and Heinrich et al (1995) shifted the focus from monitoring whole diesel particulate to the analyte of interest, ie the carbon core (termed elemental carbon).

A number of methods had been used since the early 1980's to research the carbon containing components collected on high volume sampling filters taken from air quality studies, particularly in the USA.

The carbon speciation method (controlled temperature ramping and combustion) was refined and applied to over 27,000 samples taken from more than a dozen urban and regional air quality studies (Chow et al 1993). The key factors governing separation and quantification of the various species were found to be temperature settings, rate of temperature increase, composition of the atmosphere surrounding the sample, method of optical correction for pyrolysis (char) and standardisation. Further application of the method indicated that the elemental carbon was a major indicator of diesel exhaust emissions over that of gasoline-powered vehicles (Watson 1994).

NIOSH researchers in conjunction with Sunset Laboratories proposed a thermal-optical technique for the analysis of the carbonaceous fraction of diesel particulate collected from the occupational environment (Birch 1996).

Carbon speciation analysis is carried out by placing a punched section of a quartz fibre filter in an oxygen free helium atmosphere flow furnace. The temperature is increased step wise (500^oC to 700^oC) to remove firstly all organic carbon followed then by carbonates. Pyrolised products are flushed off as CO_2, which is catalytically converted to CH_4 for detection by the FID. The oven is cooled to 25^oC, a mixture of 2% O_2/He introduced and the temperature raised in steps to 850^oC to oxidise elemental carbon which is then converted to CH_4 for detection. Monitoring laser transmission through the filter during the cycle allows minimisation of interferences caused by elemental carbon formed during the pyrolysis of organic carbon. At the end of the cycle a known volume of CH_4 is injected into the furnace for calibration purposes. Given the air volume sampled, the software calculates the concentration of elemental carbon (EC), organic carbon and total carbon (TC) in the air sample. Analysis time is less than 10 minutes per sample, with a LOD of ~0.001 mg/m^3 for either organic, elemental or total carbon. This method has achieved widespread acceptance and is now commonly referenced as NIOSH Method 5040 (NIOSH 1994).

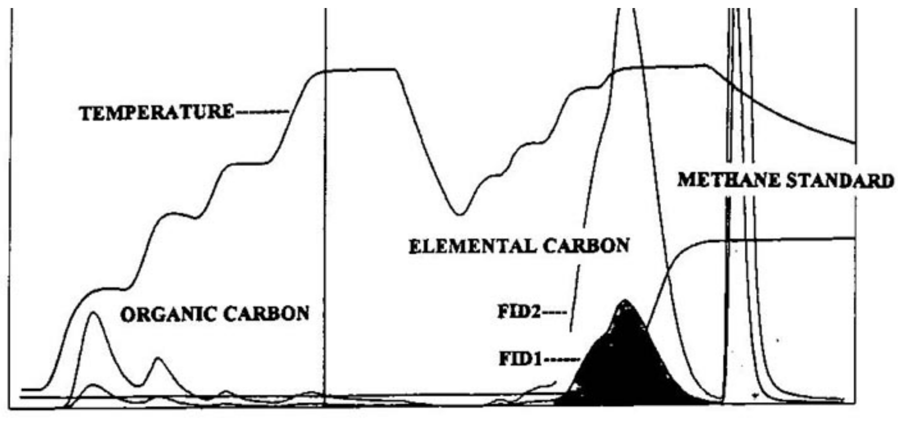

Figure 6 - Carbon Species Chromatogram *(Source: Rogers 1998)*

A similar approach has been adopted in Germany, however sampling is conducted without any size separation and analysis of combustible carbon is via a coulometric method (Dahman 1997). The lack of size selection in this method limits the method to those mining applications where combustible material (i.e. coal) is not present.

Commercial analytical instruments are available with Sunset Laboratories (Figure 7) in the USA developing instrumentation for NIOSH Method 5040 (1994), and Strohlein developing a coulometric instrument in Germany.

The NIOSH 5040 EC method requires pre conditioning of the quartz filters (800^{o}C for 2-3 hours) prior to use to remove trace organics. However experience gained in Australian research indicates that the filters supplied in bulk or in prepared cassettes, contain no measurable levels of elemental carbon. However they do contain organic carbon in the range of 5-25 µg (most likely ~15µg) per filter. After conditioning the filters in a muffle furnace, the organic carbon is readily removed, however the filters then rapidly pick up organics (not EC) from external sources such as the cassette, sealing tape etc. to around the same levels as that prior to conditioning. The experience is that conditioning is not necessary and blank subtraction from filters carried into the field adequately eliminates filter interferences for the type of samples usually collected in occupational situations.

Sampling and analysis using NIOSH 5040 has been undertaken in Australia since 1996. There is now a considerable database on the relative levels of elemental carbon, organic carbon, and total carbon (in the submicron fraction and respirable fraction) in a variety of workplaces and environmental situations. The proportions of elemental carbon, organic carbon and total carbon indicate considerable variability due to job activity and industry type.

The impression gained from Australian research is that diesel particulate is a dynamic mixture consisting of many hundreds or thousands of chemicals which is undergoing various processes of precipitation and agglomeration.

In assessing exposures via collecting the submicron fraction and carbon speciation, the occupational hygienist is attempting to measure a few indicators of a complex “aging” aerosol, the rate of change of which is influenced by a range of chemical and environmental factors.

Either elemental carbon, total carbon or submicron mass may be used as a surrogate of diesel soot exposure, however elemental carbon provides the best fingerprint of diesel particulate emissions and is relatively free of interferences.

A recent study in Canada by Verma et al (2003) also concluded that the thermo-optical method (NIOSH 5040) for elemental and organic carbon is the most valid technique to evaluate diesel particulate at the present time. Verma also supports the use of cyclones as proposed by Cohen (2002) rather than open faced sampling heads when large particles are not an issue.

Figure 7 - Sunset Laboratory Thermo Optical Organic Carbon Elemental Carbon Analyser
(Source: Coal Services Pty Ltd)

5.4 Raw Exhaust Particulate Analysis

While there has been a strong focus on the measurement of workplace exposure to diesel particulate, the measurement of raw exhaust levels has been somewhat slower. Historically, measurement of "soot" in the raw exhaust of diesel engines used in underground mines has been via gravimetric means using dilution tunnels and dynamometers (MSHA 1996), generally as part of engine approval procedures.

In the Australian coal mining industry reliance has been on the use of the Bosch Smoke Meter, otherwise known as the Sampling Opacity Meter (AS3584 – 1991). This Australian Standard required engines not to exceed specific light absorption coefficients based on the nominal gas flow (in litres/second) of the engine.

It is interesting to note that the US Bureau of Mines (Daniel 1998) investigated the use of the Bosch Smoke Meter to measure particulates from diesel engines used in mines and concluded that although good precision was obtained on a number of tests, the variability of results at different engine loads (used in their tests) was small, indicating a lack of sensitivity to changes in particulates. They concluded that the Bosch Smoke Meter was not useful at low load conditions due to a lack of adequate levels of particulates.

This conclusion appears to be in direct conflict to test requirements in the new Australian Standard (AS3584.2–2003) where the nominated test procedure requires Bosch Smoke Meter tests at no load (both low and high idle speeds) and full load.

Another approach has been adopted by Davies (2000) who modified a commercial elemental carbon analyser (Okrent 1996) to determine the levels of elemental, organic and total carbon direct from the raw exhaust of vehicles such as those used in Australian coal mines.

The instrument, originally developed for automatic collection and analysis of carbon species in air pollution studies (R & P Series 5100 Diesel Particulate Analyser), was fitted with a raw exhaust sampling probe, and a known volume of raw exhaust is collected on a quartz filter which is subsequently step heated to convert firstly organic and then elemental carbon to carbon dioxide. Analysis of the generated CO_2 is performed using a non-dispersive infrared spectroscopy and each sample calibrated against a gas standard. One Australian organisation has mounted the R&P5100 in a mobile trailer and routinely conducts field monitoring on the raw exhaust of underground diesel engines (Davies 2003) (Figure 8).

Figure 8 - Mobile Raw Exhaust Test Trailer fitted with modified Rupprect & Patashnick Series 5100 Diesel Particulate Analyser
(Source: Davies 2002)

The work carried out using this equipment has highlighted the wide variability of raw exhaust particulate concentrations from engine to engine and indicated that certain engine types generate excessive levels of particulates.

Other raw exhaust testing techniques that are available include the Tapered Element Oscillating Microbalance or TEOM (Shore 1985), and one research group has used a light scattering device in concert with a dilution tunnel.

In 2002 the NSW Department of Mineral Resources received funding to identify a suitable hand-held surrogate instrument to measure diesel particulate in the raw exhaust of underground diesel engines. Water vapour has been found to have a major effect on all light scattering instrumentation, with sophisticated sample preparation devices necessary. Dynamometer testing to date has indicated that at least two devices show sufficient promise to justify field trials, the results of which should be available in 2004.

Routine testing of CO and NOx levels in vehicle raw exhaust has proven to be beneficial in reducing workforce exposures and in many instances is a necessary part of control strategies. Recent research using instruments that are specific to diesel particulate indicates that it is just as important to test the particulate load in vehicle raw exhaust as it is to test the gaseous emissions. Unfortunately, there currently does not exist any validated hand-held device that can be used to take quick readings across the range of particulate levels commonly found and without the results being subject to considerable error. Devices do exist to measure raw exhaust diesel particulate, organic, elemental and total carbon levels, however they are research tools and require sophisticated sample preparation equipment. This area is the subject of significant investigation and a surrogate sampling device appears to be on the near horizon.

6.0 CONTROL TECHNOLOGIES

The control of diesel emission has been the subject of intense investigation and subsequent product development for decades.

Initially, the focus was on the control of gaseous emissions through technologies such as ventilation, engine tune, and catalytic converters. In the past 15 years increasing attention has been given to the control of diesel particulate, which often requires a different or additional approach than that taken for controlling CO and NOx. Compounding the overall control of exhaust emissions is the fact that CO, NOx and particulates are all interrelated and that controls that effectively reduce one component may enhance another.

While it is impossible to review every technology on the market, the following provides an overview of the broad types of control technologies that have proven to be effective in various industries.

It is important to note that experience has demonstrated that no single simple solution exists for the control of diesel particulate and in many cases combinations of technologies may be required (Pratt et al 1997).

6.1 Fuel Quality

Perhaps the most intensively investigated parameter is that of fuel quality as it was considered that improved fuel quality may offer an easy solution to the problem of particulate generation. Ryan et al (1981) summarised the properties of fuel known to effect exhaust smoke (particulates). These were boiling range, viscosity, specific gravity, aromatics, hydrogen content and cetane number.

It is interesting to note that no mention was made as to the influence of sulphur, which was not established until Ullman (1989) developed a fuel matrix which allowed the effects of sulphur content, aromatics, 90% boiling point and cetane number to be investigated.

The outcome of Ullman's research was that lowering fuel sulphur content to 0.05% resulted in a reduction of diesel particulate levels by about 10% and an increase in cetane number from 45 to 55 reduced hydrocarbons by 60%, carbon monoxide by 45%, oxides of nitrogen by 6% and particulates by 20%. Graboski (1992) provides an excellent summary of research on this topic and concludes by suggesting that control of sulphur, cetane number, aromatic content and possibly oxygen addition could reduce exhaust particulate levels by up to 25%. A high aromatics concentration increases DPM and benzo(a)pyrene formation, while a decrease in cetane number produces an increase in NOx and DPM.

Experience within the Australian mining industry has demonstrated that the introduction of low sulphur (and in many cases low aromatic) fuel significantly reduces odour and particulate levels, however in actual industrial situations, reductions in diesel particulate levels remain at about only 10-15%. This appears contrary to some research, which indicates a linear relationship between fuel sulphur content and particulate emissions particularly when very high versus low sulphur fuels are compared (Pratt et al 1997). There appears however from a practical point, lesser direct extrapolation of this relationship at the lower end of the scale, most likely due to other variable factors such as vehicle usage and associated measurement errors.

The introduction of low emission fuel (featuring amongst other things low sulphur levels) in the mining industry has reduced particulate levels, mainly eliminated eye and upper respiratory tract irritation, as well as minimising offensive odours. Unfortunately in a number of situations the inadvertent reintroduction of higher sulphur "over-the-road" diesel fuel (0.15 – 0.2% S) resulted in severe industrial action due to the return of offensive odours.

Technical problems may occur when low emission fuel is introduced into an existing operation. The change may bring about loss of power, loss of seal integrity, and lower lubricity resulting in accelerated component wear. However these problems are readily overcome given adherence to the fuel specifications and precautionary comments contained in various documents (NSW Mineral Council 1999, NSW Department of Mineral Resources 1999).

One side benefit from the use of low sulphur, low aromatic fuel has been an observable improvement in cylinder cleanliness over a period of time. This provides better combustion and thus lower emissions.

The media has highlighted the beneficial effects of a Federal Government (Fuel Quality 2000) decision to require all diesel fuel produced in Australia to have <0.05% S by 2003 and <0.005% S by 2006. The situation is not that simple as shown by the initial introduction of low sulphur fuel in Brisbane which led to a significant number of leaking fuel pumps (resultant from the shrinkage of seals) in older diesel vehicles. This was traced to a reduced level of aromatics in the fuel and future introductions in other states will be on a staged basis to prevent a recurrence of this problem.

Much has been made of the benefits of using biofuels in the reduction of diesel emissions. Such assertions have been the subject of intense research which, in many cases, indicates reductions in diesel particulate generation in excess of 30% (Watts et al 1998, Bagley et al 1998).

While this may be true, trials in underground mines have found that employee acceptance of such products is low, due to the strong odours produced in the combustion process with some bio diesel fuels. At this stage higher cost also presents a barrier for widescale acceptance, however in the future, government incentives may reduce this gap.

6.2 Ventilation

Over the past 50 years the control of gaseous emissions in underground mines has essentially relied on ventilation. This approach has been via the establishment of prescribed standards for air quantities flowing over engines so as to reduce the gas levels to less than the occupational exposure limits. In NSW and Western Australia this ventilation rate is 0.06 m^3/s/kW (NSW Coal Mines Regulation 1999, NSW Department Mineral Resources 1996, WA Department Mines & Energy, 1995) and is applied to each piece of equipment (in an additive manner) that is operating in a section of a mine. This sets the minimum ventilation rate for the operation of various combinations of diesel equipment in each section of the mine (with a minimum air flow of 3.5 m^3/s for each piece of equipment).

Pratt et al (1995) demonstrated that while the ventilation rate effectively controlled the level of gaseous emissions, the relationship of diesel particulate to ventilation in coal mines was very complex and not well understood. Furthermore it was demonstrated that large diesel engines operating in relatively small roadways at minimum airflows resulted in thermal stratification of the airway, thus potentially concentrating diesel particulate in the upper one-third of the roadway (which is approximately at head height).

For mining areas where multiple vehicles are likely to operate, the NSW Minerals Council (1999) has suggested the use of vehicle control systems or “tag boards” which effectively restrict the number of vehicles in a section of a mine so as not to overload the set ventilation rate. This system has been applied successfully in a number of underground mines throughout Australia.

The mechanism for this approach is to assign one or more tokens to each vehicle (based on the statutory airflow requirement) and to routinely measure the airflow in the mine section in question to establish how many “tokens” can reasonably be permitted to enter.

Thus, once all the tokens on the tag board are exhausted no further vehicles can enter the section until a vehicle leaves and the appropriate number of token vacancies becomes available.

In the United States a different approach is taken in that the statutory ventilation rate is determined at the engine approval stage by the Mine Safety and Health Administration (MSHA). Ventilation rates for each engine are determined by a standardised test cycle and are calculated as the quantity of air required to reduce the exhaust concentration to half the 1972 American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (a workplace exposure standard) (Dvorznak 1998). This is known as the “approval plate quantity” and allowance must be made for this quantity of air to be present for each engine in a section of a mine. While the control of gaseous emissions via ventilation is well defined, little information exists on the quantity of air necessary to control diesel particulate.

To overcome the uncertainty surrounding the selection of the correct ventilation rates to be applied, the US Government has adopted a unique approach whereby they developed a “particulate index”. This value is the quantity of air required to reduce the level of diesel particulate in the raw exhaust of an engine to 1 mg/m^3 (MSHA 1996).

While this produces an arbitrary ventilation rate for each engine design it does allow comparison of engine types in terms of their “dirtiness”. The particulate index is also used to develop a ventilation plan for each mine. This can assist mine owners in the selection of cleaner equipment.

From the available literature it is apparent that the relationship between ventilation and diesel particulate is not well understood, although attempts have been made to better understand the process via the use of computer models (Wan, Mutmansky and Ramani 1995).

At this stage ventilation remains a key control technology but it provides less latitude for controlling particulates than it does for controlling gaseous emissions, particularly in situations when engines are working under heavy load conditions. However it is more appropriate to focus on the control of diesel particulate at the source of emission rather than rely on controls that are implemented post generation.

6.3 Exhaust Treatment Devices

Post engine exhaust treatment devices have been the subject of substantial research and development over the last 40 years.

6.3.1 Catalytic Converters

The forerunner of this type of control technology was the catalytic converter and as far back as 1960 (Holz 1960) catalytic converters were recognised as being excellent in reducing the level of carbon monoxide in the exhaust of a diesel engine. At this early stage it was also recognised that catalytic converters were of limited use in reducing oxides of nitrogen and no mention was made in regard to their effect on particulates.

Catalytic converters have been used for many years to reduce gaseous emission (carbon monoxide) and hydrocarbons. Some data suggests that such devices are effective in reducing particulates, however extensive research has demonstrated reductions to be from the removal of organic carbon with the level of elemental carbon remaining unchanged.

6.3.2 Wet Scrubber Systems

In 1977 an international joint industry-government working group evaluated the benefit of catalytic converters and water scrubber tanks as used to control sparks from engines in underground coal mines (NIOSH 1982).

As predicted the review indicated there was a significant reduction in carbon monoxide, hydrocarbons and odour with catalytic converters but virtually no reduction in oxides of nitrogen or particulates.

Scrubber tanks on the other hand offered no reduction in carbon monoxide or oxides of nitrogen but some reduction (approximately 30%) in carbonaceous particulates, albeit that the surety of measurement techniques of the day may have been suspect.

This reduction in particulates using water baths has recently been confirmed for equipment used in NSW coal mines (Pratt 1995). As water baths are a statutory requirement in NSW coal mines (AS3584-1991, NSW Department of Mineral Resources 1995) it can be concluded that all vehicles fitted with such devices are achieving a 20-30% defacto reduction in particulates from that present in the raw exhaust.

Mogan (1987) investigated the use of a venturi water scrubbing system that reduced particulate levels by 65-75%, however this system has not been commercialised.

6.3.3 Regenerative Ceramic Filters

Ceramic wall flow particulate filters (Figure 9) have found increasing use in the “over-the-road” diesel transportation fleet and US and Canadian metal/non-metal mines (Waytulonis 1992). These work on the principle of trapping the carbon particulates and then using a surface catalyst, oxidising them to CO and CO_2.

However, their requirement for an exhaust temperature of greater than 400°C for effective regeneration excludes them from use in coal mines. This exclusion is based on two parameters, ie a statutory requirement that all surfaces and exhaust gases not exceed 150°C (NSW Coal Mines (underground) Regulation 1999) and the potential for uncontrolled regeneration resulting in excessive levels of carbon monoxide (Currie 1994).

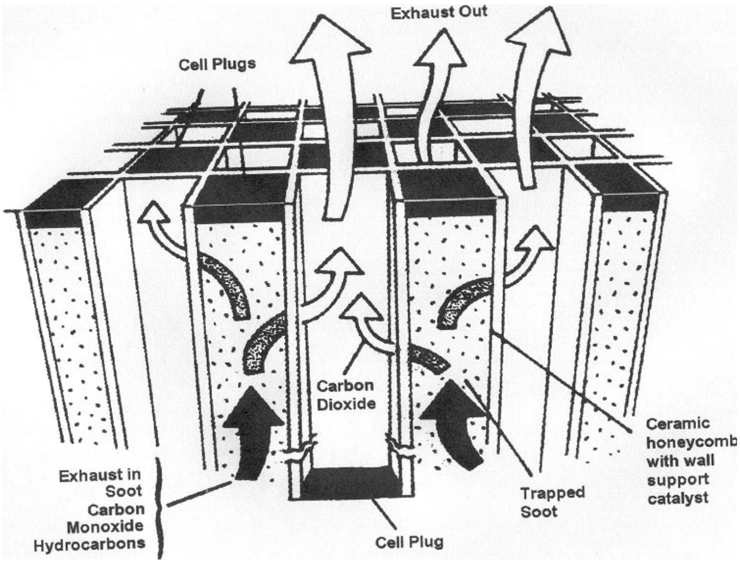

Figure 9 – Ceramic Wall Flow Particulate Filter
(Source: Colpro Pty Ltd)

These ceramic filter units can reduce particulate levels by greater than 90% but are expensive and have been historically difficult to maintain in harsh working environments. Many Australian metalliferous mines historically have moved away from using ceramic filter traps as fleet changes introduce the lower emission electronic and pneumatic controlled engines.

Improvements in technology have minimised these problems and ceramic filters are finding increasing acceptance by on-road vehicle manufacturers and in metalliferous mines as an efficient means of controlling diesel particulate. In Europe, many new diesel vehicles (including cars and buses) come fitted with such a device.

Some catalysed ceramic filters have been shown to produce increased levels of nitrogen dioxide during operation (MSHA 2002). This has resulted in such products being banned in some activities where increased NO_2 levels could be a problem, eg mining.

While regenerative exhaust filters are not an option in underground coal mines other approaches to removing the particulate from the exhaust of diesel engines have been explored.

6.3.4 Disposable Exhaust Filters

Ambs (1992) reported on the development of low temperature post scrubber tank disposable filters. Essentially these were pleated paper filters (that were commercially used as air filters for truck engines), fitted direct to the exhaust system. Reductions in diesel particulate levels, measured in the mine atmosphere, of 93-98% were achieved with a filter life of approximately 10 hours. Filter life was severely compromised by water saturation as a result of carryover from the water-filled scrubber tank (spark arrestor).

Safety concerns were also expressed by Ambs due to the fact that the filters were made of paper and if the engine shutdown system failed - resulting in a loss of water in the scrubber tank - exhaust temperatures could rise to levels where ignition of filters and collected particulate matter was possible. MSHA (2003) issued a notice recommending that paper filters not be used unless an adequate shutdown system was fitted to the vehicle and fully maintained.

Pratt et al (1995) further developed this concept by using a woven polypropylene material that melted at 170°C but did not support combustion.

This product had the added advantage of not being subject to degradation from water aerosol carried over from the scrubber tank in coal mine vehicles. If scrubber tanks are not used, then a suitable heat exchange system must be incorporated to limit the temperature of the exhaust gases to prevent filter melt or charring.

Field tests indicated reductions, as measured in an underground test station, of up to 80%. This concept has since been commercialised and is in common usage within the NSW coal mining industry (Figure 10).

Figure 10 – Disposable filter assembly fitted to an underground mining machine *(Source: Davies 2003)*

Recent research by Davies (2003) has demonstrated that these filters can reduce elemental carbon levels in the raw exhaust of diesel engines by approximately 85%. Improvements in filter life have also been obtained by the reduction of pleat numbers and the use of internal glue lines to keep the filter pleats separated so as to increase the effective surface area. The effectiveness of this approach is demonstrated in Figure 11 where the media from a new and used filter (11.8 hours operation) are compared.

Figure 11 – Comparison of New (right) and Used (left) Filter Media
(Source: Davies 2003)

These type of filters have also been used in non-mining situations (eg diesel forklifts in shipping containers) with apparent success.

6.3.5 Dilution - Dispersion Systems

Exhaust dispersion devices have, in the past, been used within the mining industry as a control device (Lowndes and Moloney 1996). While a tenfold dilution of raw exhaust emissions has been recorded, the fact remains that this is a dilution rather than a removal process and thus these devices do not alter the amount of diesel particulate in the general mine atmosphere.

6.4 Engine Design and Maintenance

Perhaps the two areas that offer the greatest possibility for reduction in diesel particulate are engine design (for controlled fuel-air supply and efficient combustion) and engine maintenance (to ensure optimal fuel air mix for optimal combustion and power conditions).

6.4.1 *Engine Design*

Waytulonis (1992) reports on research at the US Bureau of Mines where the emissions from a normally aspirated diesel engine (Caterpillar 3304) of 1979 vintage were compared to a 1991 electronically controlled engine (DDC 8V-92TA).

Under the same test conditions the Caterpillar 3304 engine produced an average particulate level of 0.11 g/MJ while the DDC engine only produced 0.052 g/MJ; a reduction of approximately 50%. Electronic controlled engines achieve this reduction in particulates by continually optimising the fuel injection timing and rate to match each power requirement during the operation cycle of the engine. In essence such electronically controlled engines are always in tune with load requirements.

A recent study in a US salt mine (Bagley et al 2002), where comparisons were made between naturally aspirated engines and new generation electronic controlled engines, found major decreases (60%) in total and elemental carbon when electronically controlled engines were used. Moreover, there was no evidence of increased production of nanoparticles with the use of low emission engines. Also the PAH and biological (mutagenic) activity levels also showed large decreases with use of the electronically controlled diesel engines (by up to about 90% and 65% respectively).

Overall, use of electronically controlled, modern diesel engines with a low sulphur fuel in an underground mine, resulted in large reductions in diesel particulate and related components. The measured potentially health related components showed similar reductions.

These newer designed engines are common within "over-the-road" vehicles and the metalliferous mining industry but are not presently allowed in underground coal mines due to their lack of intrinsic safety features.

Consequently, the coal industry continues to use 30-year old designed engines that emit relatively high levels of diesel particulate.

The substantial benefits of newer designed engines (albeit not electronically controlled) has been demonstrated by Davies (2000) who compared the emissions from mine transport vehicles to that of commercial over-the-road vehicles. In this case a KIA diesel engine (50 kW) was compared with a Toyota Landcruiser Series 75 engine (95 kW) with the total carbon output of the KIA engine ranging from 0.33-1.7 g/kWh to 0.005-0.09 g/kWhr for the Toyota engine.

While Davies (2000) acknowledges that such direct comparisons in the field are difficult due to the different engine system used in mine vehicles, it is not difficult to imagine that newer more fuel-efficient design engines will offer substantial benefits in emission reduction.

This also appears to be the view of the European Union and US EPA who now require engine manufacturers to introduce new technology engines on a tiered scale.

For heavy-duty highway engines the US EPA requires particulate matter generation to not exceed 0.01 g/bhp-hr (0.013 g/kWhr) for all engines produced after 2007. Non-road engines (generators, etc) have been treated more leniently but are still required to meet new, more stringent, standards.

6.4.2 Engine Maintenance

The effects of poor maintenance on exhaust emissions on engines used in the mining industry have been recognised for over 40 years (Holz 1960), however it was Waytulonis (1985) who demonstrated how a restriction in the air intake of 13 kPa and over-fuelling by 20% could result in an increase in particulate generation of 1038%.

While such a severe inlet restriction coupled with a massive degree of over-fuelling is likely to be rare, he did conclude that the single faults that increase particulates were intake restriction (+44 to +164%) and over-fuelling (+125% to +173%). A key factor that was also identified was that in the absence of severe faults or mal-adjustments, exhaust emission quality did not degrade excessively during the initial 4,000 hours in service.

After this time engines typically developed the following trends; carbon monoxide increased, hydrocarbons increased, oxides of nitrogen decreased and particulates increased. Waytulonis (1985) examined a total of 13 engines from five US mines, however only mines with a perceived good maintenance record were willing to supply engines for assessment. The lack of engines from mines with lesser developed maintenance programmes may have resulted in Waytulonis under-stating the effects of maintenance on diesel particulate control.

A major study in Canada (McGinn 1998) within the underground metalliferous mining industry, demonstrated that a well planned and executed maintenance programme can reduce gaseous emissions (carbon monoxide) by as much as 65% and particulate emissions by up to 55%. Individual issues which contributed to elevated emission levels included leaks in the intake air system, defective turbochargers, non serviceable exhaust systems, poorly tuned fuel injection systems and poorly designed cooling systems. McGinn (1998) concluded that maintenance of the fuel injection system made the largest single difference to exhaust emissions (both gaseous and particulate).

Davies (2000) explored the effect of maintenance on diesel particulate emissions on one diesel machine used in the fleet of an operating coal mine. In this case the vehicle was removed from the fleet and the raw exhaust was measured for total carbon content and a value of 0.84-1.4 g/kWhr recorded.

The inlet flame trap was removed and cleaned in an ultrasonic bath for approximately 15 minutes, dried, replaced and the exhaust re-measured under the same load conditions. The total carbon was reduced to 0.38-0.40 g/kWhr, a reduction of 55-71%.

A recent study within the NSW coal mining industry by Davies (2003) in which the raw exhaust of 66 diesel engines was monitored for elemental carbon (using the R&P Series 5100 Diesel Particulate Analyser), found seven engines with elevated EC concentrations. Further examination of these engines traced the elevated levels to blocked water baths (flame arrestors) on two engines, worn injectors on another two engines and the remaining three engines are still under investigation.

Recently MSHA (2003) has published guidance on the maintenance of diesel equipment used in underground coal mines to minimise diesel particulate generation. Recommended actions include checking for:

- Clogged air filters and leaks in the air intake system.
- Correct fuel injection rate.
- Correct fuel injection timing.
- Correct operation of all fuel injection system components (fuel filters, water separators, fuel pumps and fuel injectors).
- Correct operation of electronic engine controls.
- High oil consumption.
- Increased carbon monoxide emissions.
- Clogged disposable diesel exhaust filters.

These factors have also been found to be a major determinate of poor emission levels in the Australian mining industry (Pratt et al 1995).

While this guidance has specifically been targeted at the mining industry, many of the recommendations hold equally true for other diesel equipment. The effectiveness of good maintenance programmes cannot be understated and it should be recognised that diesel engines have an effective usable life beyond which emission generation increases rapidly. The US EPA has suggested for non-road engines that this is 10 years, however evidence supporting such a definitive time is unclear.

6.5 Enclosed Cabins

The use of air-conditioned cabins on some diesel equipment presents a means of reducing operator exposure to DPM. A 30% to 87% reduction can be achieved, dependent on a combination of the design and condition of the filtering system, the proportion of recycled air and the quality of the door and window seals. While this limits exposure of the operator, many other work groups will remain exposed unless an overall emission management plan is implemented.

6.6 Respiratory Protection

The use of respiratory protective equipment should not be considered as a primary method of control but can assist in reducing employee exposure in specific situations. Fundamental occupational hygiene practice is to eliminate or minimise hazards before resorting to personal protective equipment. In respect to diesel particulate, many control technologies have a considerable lead time for implementation and in these situations the use of respiratory protection as an interim measure would be acceptable.

A number of equipment suppliers have introduced specific respirators for diesel particulate or similar aerosols. Experience has demonstrated that the use of P1 and P2 dust respirators is effective in minimising employee exposures.

In such cases selection, use and maintenance of respiratory protection should be in accordance with that specified in Australian Standard AS1715 (1994).

7.0 OVERVIEW

Diesel particulate has been found to consist primarily of small particles (15 – 30 mm) that agglomerate together to form larger particles which are typically less than 1 μm in diameter. The structure is essentially a carbonaceous/graphitic nucleus surrounded by organic matter with traces of inorganic compounds. Such particles are in the lower end of the respirable size range and thus can be transported to the alveoli.

The potential for such fine particles to give rise to adverse health effects in the occupational situation has been recognized for the past 25 years. However even to this day no definitive or applicable toxicological dose response relationship for malignant or non-malignant health potential has been established.

There is now more than 30 published epidemiological studies analysing the health outcomes or lack of outcome from exposure to diesel particulate. More than half of the studies have produced negative outcomes in that they do not find an elevated risk of lung cancer. For the studies that indicate an increased risk, most lack information on major confounders for lung cancer such as tobacco smoking, asbestos exposure and relative degree of potential exposure to diesel exhaust. None of the 30 plus studies is supported by actual exposure data relevant to the cohorts.

A diversity of interpretations have been made by various authors in reviewing these epidemiological studies, including those that have combined various groups in meta-analysis. The interpretation appears to depend on how the negative studies and statistical uncertainties are treated.

While the epidemiology of diesel particulate remains unclear, and is unlikely to be resolved in the near future, there is no doubt as to the irritant nature of diesel emissions (including particulate) in confined atmospheres including that found in mines. On this basis the control of such emissions to minimise irritation in workplaces may in turn reduce the potential for any long-term health effects below that which is detectable.

Methods for the quantification of employee exposure to diesel particulate have been developing over approximately 30 years. The most advanced and specific method involves capturing the submicron fraction of the workplace aerosol and then determining the amount of the core component of diesel particulate (elemental carbon). Recent commercial developments provide ease in routine submicron sampling using a single use cassette fitted to a respirable aerosol cyclone. Sample analysis is best conducted using NIOSH method 5040 for determination of carbon species (especially elemental carbon), however care needs to be exercised to minimise errors due to sampling, blank filter interpretation and instrument operating parameters.

The accurate measurement of diesel particulate in the raw exhaust of engines is currently possible using research-based analytical equipment. Considerable research is underway to identify a portable hand-monitoring device, which has acceptable accuracy in the presence of high levels of water vapour typically found in the raw exhaust of diesel engines. A number of instruments and technologies appear promising with more definitive data likely to be available within the next 12 months.

Currently no workplace exposure standard exists within Australia, however extensive experience in the mining industry indicates that if exposures are maintained below 0.1 mg/m^3 elemental carbon (approximately 0.2 mg/m^3 diesel particulate), employee irritation is significantly minimised.

There is no consistent toxicological or epidemiological evidence to suggest that adoption of such an exposure value would protect against long-term adverse health effects if such effects do arise from exposure to diesel particulate.

While a number of effective and practical control technologies for diesel particulate have been identified, good engine maintenance and emission controls are essential. Proven technologies to control diesel particulate generation or employee exposure are currently available, however in the majority of cases no single simple solution exists. Each situation needs to be evaluated on its merits and a resultant management plan developed. In some cases this may be as simple as redirecting an exhaust away from personnel and in others it may be the retrofit of more sophisticated control technologies. The new generation electronically controlled engines appear to provide the best long-term approach to emission and hence exposure reductions. However, there may still be a need to use other control technologies with these engines, dependent on the level of control that is ultimately required by regulatory authorities.

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