UNIVERSITY
OF WOLLONGONG
AUSTRALIA

Faculty of Social Sciences

School of Health and Society

Respiratory Protection: Do PAPRs adequately protect workers against DPM?

CSHST 20641

Final Report

January 2019

Jane L. Whitelaw

Kerrie A. Burton

Brian Davies

Alison L. Jones

Executive Summary

Exposure to diesel exhaust emissions, of which diesel particulate matter (DPM) is a major component, can cause adverse health impacts including lung cancer, cardiovascular and irritant effects (WHO 2012). Management of underground worker's health by improved controls to mitigate exposure to DPM has been highlighted as a research priority for underground mining (ACARP research priorities 2018, Coal Services Health & Safety Trust 2018).

Although the lowest level of the Hierarchy of Control, personal respiratory protective devices are a common control measure to mitigate worker exposure against the damaging health impacts of diesel emissions and to be effective they need to provide adequate filtration.

The effectiveness of respiratory protection is evaluated in accordance with AS/NZS 1716. The current respiratory certification testing protocols do not evaluate filtration of oily particles or penetration across the spectrum of particles in the ultrafine region and hence may not include the smaller sized nanoparticles that may be the most penetrating, and suspected of being responsible for many of the adverse health effects. Initial findings of the particle size testing show high particle penetration in the nanoparticle size fractions known to have respiratory and cardiovascular effects.

Recent research undertaken by Burton, Whitelaw, Davies and Jones (2014-2017) evaluated penetration of DPM through eight commonly used respirator filters, at the flow rate designated in the standard, as well as at two higher flow rates representative of medium to heavy work. The results demonstrated that when these respirators were challenged with DPM, measured as elemental carbon, the filtering efficiency assumed by P2 certification (<6%) in Australia was not achieved for some respirators. DPM penetration through some of the P2 respirators commonly used in mining; failed to meet the filtering efficiency for P2 certification in Australia after a reasonably short wear time.

Recent studies on negative pressure air purifying respirators by Burton et al (2016, 2017) found that even with correct fit and wear time; workers may not be adequate protected from DPM in all circumstances, particularly at high work rates.

Powered air purifying respirators (PAPRs) are also used extensively in some workplaces, and may be used increasingly due to changing standards on recommendations on work rates outlined in ISO/TS 16976-4:2012 and greater focus on fit testing compliance and difficulties

with implementing clean shaven policies. Without data on PAPR filtration efficiency against DPM there is uncertainty around whether wearers of these devices are adequately protected.

Thus a study was designed to determine whether Powered Air Purifying Respirators (PAPRs) filters approved and used in Australian workplaces effectively protect workers from exposure to DPM, and whether current protocols specified in the Australian Standard for respiratory protective devices (Standards Australia International Ltd and Standards New Zealand, 2012) ensure worker health is protected.

The aims of this study were to:

1. Determine whether three PAPRs currently used in the Mining industry provide adequate protection for workers exposed to carcinogenic DPM
2. Evaluate these currently used PAPRs against paraffin oil to predict their performance in oily environments, and
3. Determine the Most Penetrating Particle Size range (MPPS) through these PAPR filters.

Key Findings

All three filters failed to meet their rated filtering efficiency when evaluated for Elemental Carbon (EC), Total Carbon (TC) and Particle Number Count (PNC).

This suggests that limitations in the current test protocols for filtering efficiency specified in AS/NZS 1716, may mean workers are not adequately protected against DPM, under all circumstances of diesel generated particles.

The implication that the current test methodology has some limitations has been acknowledged by Standards Australia in the preface to AS/NZS 1716; with notice given of intent to adopt the ISO series of respirator standards in the next revision of AS/NZS 1716. In the interim, it is recommended that Australian manufacturers and suppliers acknowledge the international test criteria which distinguishes between oil and non-oil based substances when recommending respiratory protection for DPM, given the published research findings that filter penetration may differ when challenged with DPM (Janssen, 2003, Burton et al., 2016).

Given the current work to develop aligned International Standards it is important that these standards adequately ensure protection against hazardous contaminants such as DPM, by utilising test protocols that are representative of the hazardous contaminants and consistent with worker respirator usage. It should be noted that draft ISO standards specify NaCl or Paraffin Oil as a challenge aerosol, but do not specify under what scenarios each should be used. They do however, require selection of an appropriate respirator with consideration of work rate. When combined with previous challenge testing (Burton et al 2016 CSHST); the results of this study indicate that Paraffin Oil provides a more conservative estimate of exposure to DPM than NaCl and hence the additional utilization of an oily agent in standards methodology would be more protective of worker health.

It is envisaged that the findings from this research will assist the development of improved Australian and International standards relating to the selection and evaluation of respiratory protection equipment to control DPM exposures to better manage the health risk for personnel exposed to this workplace carcinogen. The findings of this study will inform employers and users of the limitations in selection of respiratory protection and contribute to manufacturers' and suppliers' knowledge in the selection of respirator filters for use against DPM and protection of human health.

TABLE OF CONTENTS

TABLE OF TABLES

TABLES OF FIGURES

1 INTRODUCTION

Diesel engines are used extensively in the mining industry, potentially exposing workers to diesel emissions. These emissions are known to cause irritant effects as well as being confirmed human carcinogens (World Health Organisation, 2013) and they are also associated with an increase in cardiovascular mortality and morbidity (Brook et al., 2010).

Diesel emissions can be separated into two components: DPM and a gaseous component. This study examines the particulate component only i.e. DPM.

As diesel engine technology and controls improve, it is recogised that particle mass is decreasing in diesel engine emissions, however the number of smaller sized particles is increasing (Hesterberg et al., 2011, Maricq, 2007). A significant portion of the DPM are ultrafine particles in the nanometer range and this is an area of emerging health concern (Karn et al., 2005; Borm et al., 2006; Liu et al,2006 ; Nel et al.,2006.;Renn & Roco, 2006;Bakand et al., 2012.

Although the last line of defense in the hierarchy of control, respiratory protection is widely used to mitigate exposure to DPM to supplement other management strategies or where higher order controls are not effective (Standards Australia International Ltd and Standards New Zealand, 2009, Cherrie, 2009).

Recent research undertaken by Burton, Whitelaw and Jones (CSHST 2015-16 Project 20634 & WorkCover Applied Research grant 2015/005356) evaluated penetration of DPM through eight commonly used respirator filters, at the flow rate designated in the standard, as well as at two higher flow rates representative of medium to heavy work. The results indicate that when challenged with DPM, measured as elemental carbon, the filtering efficiency assumed by P2 certification (<6%) in Australia was not achieved for some respirators. We found that DPM penetration through some of the P2 respirators commonly used in mining failed to meet the filtering efficiency for P2 certification in Australia (ie > 6%) after a reasonably short wear time.

These limitations are confirmed by US and European studies which reported that not all tested filters met the filtering efficiency requirements outlined in the relevant standards when challenged with diesel engine emissions (Penconek et al., 2013, Janssen and Bidwell, 2006)

AS/NZS 1715 (Standards Australia International Ltd and Standards New Zealand, 2009) provides guidance on the appropriate selection of respiratory protection. Since DPM is thermally generated by the diesel engine combustion processes, the standard AS/NZS1715 recommends a minimum P2 half face-piece respirator for worker exposures up to 10 times the occupational exposure standard or a powered air purifying device (PAPR) with a minimum P2 filter up to fifty times the occupational exposure standard. (Standards Australia International Ltd and Standards New Zealand, 2009).

Minimum certification requirements for air-purifying particulate respirators include testing penetration through the filter media to evaluate filtering efficiency using prescribed challenge aerosols and flow rates (Standards Australia International Ltd and Standards New Zealand, 2012). Internationally, test protocols in standards to evaluate filtering efficiency differ in relation to challenge aerosols and flow rates (CEN, 2001, Code of Federal Regulations, 1995). At this point in time Standards Australia approved respirator filters are not challenged with workplace contaminants representative of diesel engine emissions.

Powered air purifying respirators (PAPRs) are also used in mining workplaces and may be used increasingly due to changing standards on recommendations on work rates outlined in ISO/TS 16976-4:2012 and higher reliance due to greater emphasis on fit testing and difficulties with implementing.

To date, there are no published studies evaluating filtering efficiency of PAPRs against diesel engine emissions and without this information, there is uncertainty around whether wearers of these devices are adequately protected.

1.1 Key Research Objectives

This study was conducted to determine whether currently utilised powered air purifying respirators (PAPRs) effectively filter out DPM and provide worker protection. Three PAPR filters used in mining workplaces were challenged with DPM and the Elemental Carbon (EC) and the number and sizes of particles that penetrate the filters (by particle number count – PNC) were evaluated.

Further analysis of the three filter models was undertaken using current NaCl and Paraffin standards certified methods and challenge aerosols, to enable comparison with the study results.

The effectiveness of respiratory protection was evaluated in accordance with AS/NZS 1716.

1.2 Limitations and Constraints of the Study

It is well documented that diesel exhaust emissions vary in characteristics based on variables such as engine design, load, exhaust treatments and operating condition as well as the type of fuel used. This research was conducted for one diesel engine. As such the reported findings represent the conditions under which the testing was conducted, including operating load and fuel source. Therefore, these factors may contribute to the variability between the measured penetrations for the various respirator filter models.

An EC/TC ratio of approximately 0.78 was reported for nine coal mines in Australia (Noll et al., 2014), which is comparable with the EC/TC ratio of 0.70 measured for this study, therefore the results would be consistent for those seen in Australian industries and workplaces that may require respiratory protection.

The study was confined to the efficiency of PAPR filters only at one flow rate and did not consider other factors which influence the level of protection provided to users, such as Total Inward Leakage (TIL).

The particulate matter component of diesel engine emissions (DPM) was the focus of the study, and gaseous components of the emissions, such as carbon monoxide, and nitrogen dioxide, were not evaluated.

The number of replicates for each filter and flow rate was limited to 6 replicates per filter model, leading to some PNC results with wide confidence intervals.

The International approach for measuring particle number was adopted, hence data below 23nm was excluded (Swiss Association for Standardisation, 2014). Data below this size range are not considered reliable due to artificially generated small particles from the thermal dilution system used in the instrumentation which are not from the diesel engine. This issue has been the subject of research and new technology is evolving to address this issue (Kasper, 2004).

1.3 Statement of Assumptions

Air pressure was not measured inside the experimental dilution chamber, however it was assumed to be consistent with local weather data for the purpose of determining compliance with the Standards specified limits and converting the measured sampling volumes to Standard Temperature and Pressure.

2 CURRENT LEGISLATION AND STANDARDS

Safe Work Australia has not designated an occupational exposure standard for DPM (SafeWork Australia, 2016). DPM is not specifically referenced in the Model Work Health and Safety Regulations. However it is a relevant consideration under the requirements of Part 3.1 Managing Risks to Health and Safety; specifically Clause 34 where a duty holder must identify reasonably foreseeable risks to health and safety and Clause 35 where a duty holder must eliminate those risks or minimise those risks as far as reasonably practicable SafeWork Australia (2016).

The Australian Institute of Occupational Hygienists AIOH (2013) recommends "limiting worker exposure to DPM to as low as reasonably practicable (ALARP) blow an 8hr time weighted average (TWA) guidance value of no more than 0.1 milligrams (mg) submicron fraction elemental carbon in each cubic metre (m^3) of air. In addition, a TWA value of 0.05mg/m^3 should be applied as an action level which triggers investigation of the sources of exposure and implementation of suitable control strategies"

Various Australian mining industry regulatory bodies have a recommended exposure standard of 0.1mg/m^3 EC including NSW under MDG 29 NSW Department of Primary Industries (2008) NSW Trade and Investment Mine Safety (2013); Queensland Department of Natural Resources and Mines (2012) and in Western Australia the Department of Mines and Petroleum Safety (Department of Mines and Petroleum, 2013).

2.1 Respiratory Protection to Mitigate Exposure to DPM

2.1.1 Selection

DPM consists of thermally generated particles, hence a respirator capable of filtering these smaller particles is required. AS/NZS 1715 states that a P2 or P3 filter is required, and in a PAPR these will provide a minimum protection factor of 50 times the occupational exposure standard for a P2 filter, and 100 times the exposure standard for a P3 filter.

Technical representatives from three Australian manufacturers and Occupational Hygienists in the Mining Industry were approached for their advice on PAPR/filter combinations currently used for protection against DPM in the mining industry. The results are summarised in Table 2.1.

Table 2.1 PAPR/filter combinations used or recommended for protection against DPM in the mining industry.

Supplier	PAPR Unit	Filter	Protection Factor
3M Australia	3M™ Airstream™ Powered Air Purifying Respirator (PAPR) System	060-23-11PAUS	50
Dräger Safety Australia	Dräger X-plore®8000	AR HE-F001	100
CleanSpace	CleanSpace2	PAF-0037	100

2.1.2 Current test protocols to evaluate filtering efficiency

Minimum certification requirements for air-purifying particulate respirators include testing penetration through the filter media to evaluate filtering efficiency, using prescribed challenge aerosols and flow rates (Standards Australia International Ltd and Standards New Zealand, 2012, Code of Federal Regulations, 1995, CEN, 2001).

In Australia, respiratory protection is evaluated in accordance with AS/NZS 1716 (Standards Australia International Ltd and Standards New Zealand, 2012). A number of performance requirements are evaluated to gain Australian Standards approval, including simulated rough usage and wear treatment, inhalation resistance and filtering efficiency. Filtration efficiency is evaluated by determining Total Inward Leakage (TIL). TIL is defined as the combination of contaminated air that leaks through the respirator from various sources, including face seal, valves and gaskets and penetration through the filter media. It is measured using NaCl aerosol particles as described in Appendix D of AS / NZS 1716 (Standards Australia International Ltd and Standards New Zealand, 2012).

For particulate filters, filtering efficiency is determined by challenging the filter with aerosolised NaCl and measuring the concentration before and after the filter. Penetration of particles through the filter media is tested in accordance with Appendix I of AS/NZS 1716 (Standards Australia International Ltd and Standards New Zealand, 2012) and calculated using the following equation:

$$Penetration = \frac{Concentration\ after\ filter}{Concentration\ before\ filter}\ x\ 100\%$$

A P2 rating for the PAPR filter is achieved if the penetration through the filter media is less than 1% and for P3 less than 0.05% (i.e. filtering efficiency is greater than 99% and 99.95% respectively).

Internationally, test protocols in standards to evaluate filtering efficiency differ in relation to challenge aerosols and flow rates. US test certification protocols differentiate between oil and non-oil based contaminants, and specify use of di-octyl phthalate (DOP) as the challenge aerosol for oil based contaminants like DPM (Code of Federal Regulations, 1995). NIOSH R series filters are rated as oil proof, and P series filters as oil resistant for short periods, whilst N series rated filters would not be recommended for oil based contaminants. European Standards require filters to be tested with both NaCl and Paraffin Oil (CEN, 2001). ISO are currently developing respiratory protection standards, with published drafts available for review and comment. The aim of these new standards is to align respirator testing protocols and specifications internationally (ISO, 2013, ISO, 2012). Consistent with European Standards, NaCl or Paraffin Oil are recommended as the challenge aerosols for certification testing (Standards Australia Limited, 2015).

2.1.3 Limitations of current standards testing protocols

The Diesel Exhaust in Miner's study reported on use of protective equipment for workers. Whilst this information was obtained primarily from interviews with next of kin and hence does not provide specific and accurate data, the authors observed that "*subjects who reported having used protective equipment appeared to experience risks similar to the estimates for all workers combined*" (Silverman et al., 2012). This finding could be attributed to several causes, however highlights important factors in the use of protective equipment, including selection of the correct respirator and ensuring it is fitted correctly to be effective against the agents associated with the adverse health outcome.

Filtering efficiency is tested using a designated challenge aerosol that is not specific to the contaminant for which protection is being sought. DPM differs from NaCl in both chemical structure and morphology. NaCl particles are either single crystals or compact agglomerations of crystals (Cho et al., 2011) whilst DPM has various spherical and agglomerated particles

(Davies and Rogers, 2004) which may have different mechanisms of filtration and hence potentially varying penetrations through the filter.

The Institut de recherche Robert-Sauvé en santé et en Sécurité du Travail (IRSST) reported on a procedure developed to measure the effectiveness of respirator filters against nanoparticles Haghighat et al. (2012). This study identified that penetration through the filter media at variable flow rates impacted on filtration performance. By challenging the filter media with nanoparticles of NaCl, the researchers measured the Most Penetrating Particle Size (MPPS) for various filter media over a period of time and found that it varied with flow rate, properties of the filter media and length of exposure.

Penetration has been shown to increase at the most penetrating particle size at higher flow rates, in a study conducted by measuring Total inward leakage for N95 and P100 cartridge respirators. The authors conclude that "*most penetrating particle size should be considered as a key factor in the development of respirator standards and recommendations for protection against nanoparticles*" Rengasamy et al. (2013).

As outlined above, filtering efficiency is tested using a designated challenge aerosol that is not specific to the contaminant for which protection is being sought. DPM differs from NaCl in many respects. AS/NZS 1716 states that the "sodium chloride aerosol particles used in this test are much smaller than particles typically found in the workplace." Appendix L of the standard describes that the aerosolised particles are in the size range 0.02-2 µm equivalent diameter with a mass median particle diameter of 0.3-0.6 µm Standards Australia International (Standards Australia International Ltd and Standards New Zealand 2009). Most particles in the nucleation phase of DPM formation, which range in diameter from 0.1-0.3 µm, are below the mass median particle diameter of NaCl.

Eninger and colleagues (Eninger, Honda, Reponen, et al. 2008) evaluate whether NIOSH certification processes were adequate for ultrafine particles. They reported that whilst the challenge aerosols do contain particles in the ultrafine size fraction, the limit of detection excludes the smaller particles in the range. The authors stated that "*68% (by count) and 8% (by mass) of the challenge NaCl aerosol particles below 100 nm diameter do not significantly contribute to the filter penetration measurement*". Figure 2.1 shows the particle size of NaCl and dioctyl phthalate, which are typically used in Australian, NIOSH and EN testing protocols, as well as the detection limit of the photometer used to measure concentration of these particles.

The size range of dioctyl phthalate is 0.185 ± 0.2 µm, which also does not provide assessment of filtering efficiency of smaller diameter particles. These smaller diameter particles are known to penetrate deeper into the alveolar reaches of the lungs and postulated to be a pathway for adverse cardiovascular affects. It is important to confirm that filters are efficient at preventing inhalation of these smaller particles.

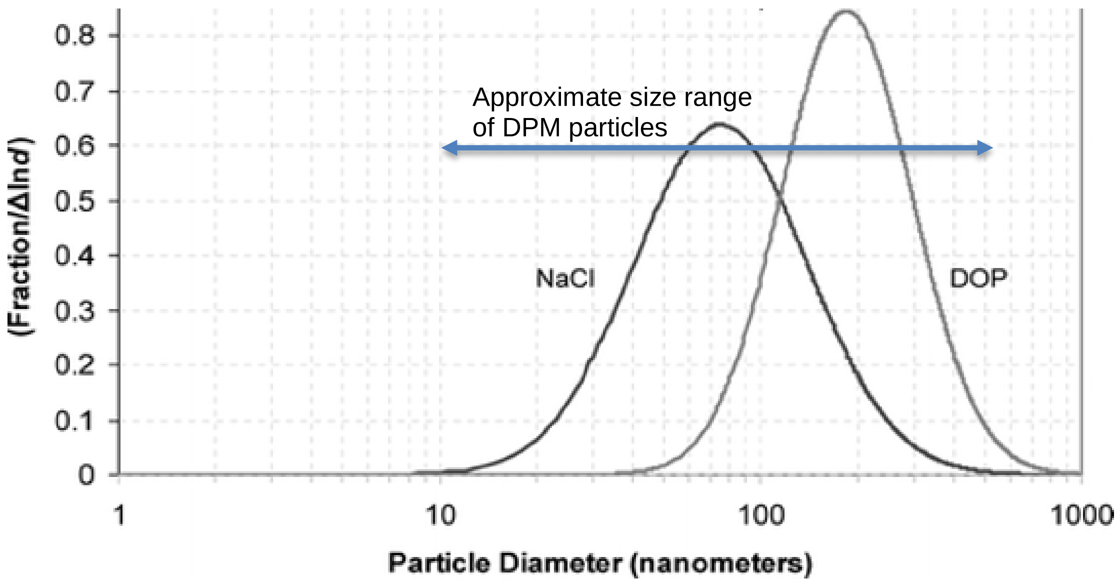

Figure 2.1 Challenge aerosol particle size distributions (by count) and photometer limit of detection, showing size range of DPM particles, adapted from (Eninger, Honda, Reponen, et al. 2008)

2.2 Evaluation of Research Methods

2.2.1 Measurement of DPM

Given the complex composition of DPM and the varying physical and chemical characteristics, there are a variety of methods available to assess exposure. Measurement of EC concentration by NIOSH 5040, is currently a preferred option because EC is a major constituent of the particulate mass, can be quantified at low levels and in most workplaces the source of EC is diesel (Birch and Cary, 1996, Bunn et al., 2002, Liukonen et al., 2002).

EC has also been utilized as a marker for potential adverse health outcomes and has an exposure standard in Australian mining regulations based on minimizing these adverse health outcomes.

The measurement of EC relies on a Thermo-optical method of analysis (NIOSH, 2016). This analysis reports both EC and TC.

2.2.2 Measurement of Particle Number Count

There are several measurement techniques available to describe diesel engine emissions which reference particle number count. One such system is a Scanning Mobility Particle Sizer (SMPS) with Condensation Particle Counter (CPC). This covers the size range of interest, however, has a 3minute scan time. The alternative instrument the Engine Exhaust Particle Sizer (EEPS) which was chosen for this study has a faster resolution time and the size range covers the size range of diesel emissions (Alföldy et al., 2009).

Currently there are no occupational exposure standards specific to metrics such as particle number, surface area and particle size which are also characteristics associated with exposure to DPM. Therefore, whilst measurement of these parameters is feasible, there are no guidelines to determine whether the measured exposures are acceptable, making interpretation of the results difficult.

3 METHODOLOGY

A method based on the protocol for testing filtering efficiency of particulate filters outlined in AS1716 Appendices I and L (Standards Australia International Ltd and Standards New Zealand, 2012), was developed in order to evaluate the key research objectives. Reference was also made to Australian Standards AS ISO16900.3:2015 Determination of Particle Filter Penetration (Standards Australia 2015). Unlike these referenced standards, DPM was used in place of sodium chloride as the challenge aerosol. The sampling methodology required the use of a purpose designed and built experimental chamber.

3.1 Respirator Filter Media

Three respirator filters (see Table 3.1) recommended by manufacturers and mining professionals to protect workers from exposure to DPM were tested; one P2 and two P3. One of these contained an activated carbon layer which is designed to reduce exposure to nuisance levels (i.e. below the occupational exposure standard) of organic vapour and odour.

Table 3.1 Selected PAPR Filter Media

PAPR	Filter Model	AS/NZS Rating	Photo of Filter
3M™ Airstream™ Powered Air Purifying Respirator (PAPR) System	060-23-11PAUS	PAPR-P2 OV AUS 99% rated efficiency for particulate filtration and nuisance level for organic vapours	
Dräger X-plore®8000	AR HE-F001	PAPR-P3 99.95% rated efficiency for particulate filtration	
CleanSpace2	PAF-0037	PAPR-P 99.95% rated efficiency for particulate filtration 3	

3.2 Generation of Diesel Engine Emissions

A Detroit D706 LTE 4.4L Tier 3 diesel engine with hydraulic load system was used to generate DPM. The engine was operated at peak torque (1400RPM) and a hydraulic load of 2000PSI. This engine is of similar capacity and design to many of the engines used in mining operations. The engine was fuelled with Shell Diesel obtained from the local service station, containing <10ppm Fuel Sulphur content.

3.3 Experimental Chamber

The experimental chamber developed in a previous study (Burton, 2016) was utilised for this study.

3.4 Sampling Equipment

3.4.1 Measurement of EC and TC

SKC AirChek pumps were used to draw air through the SKC225-401 37mm preloaded 3 piece cassettes as outlined in NIOSH 5040 (NIOSH, 2016). The pumps operated at a flow rate of approximately 5L/min, with accuracy of ±1%, as measured by a calibrated BIOS Defender 510. Blank samples were also collected each sampling day and submitted for analysis with the test samples.

Samples were analysed for EC and TC by Coal Mines Technical Services using the principles of NIOSH Method 5040 (NIOSH, 2016).

3.4.2 Measurement of Particle Number Count (PNC)

A TSI Model 3090 Engine Exhaust Particle Sizer (EEPS) was used to measure particle number count. The emissions were diluted by a calibrated MD19-3E rotating disk diluter integrated in the ASET15-1 Air Supply /Evaporation Tube, so that the emissions were within optimal parameters of the EEPS. A stainless steel probe with air inlet holes was inserted into the chamber and connected to the diluter probe and subsequently the EEPS via a stainless steel 3-way valve and heated sampling line.

3.5 Sampling Protocol and Conditions

All equipment was confirmed to be within calibration specifications throughout the sampling.

The respirator filters were placed inside the chamber sealed to purpose built/engineered adaptor plates.

Diesel exhaust from the engine was drawn into the chamber from the sample points both pre and post catalytic converter. The aim was to achieve a prefilter concentration of 1.0mg/m^3 EC in the chamber, equivalent to the rated protection factor of the respirator filters, i.e. ten times the Occupational Exposure Standard of 0.1mg/m^3. A vacuum pump connected to a stainless steel inlet at the base of the chamber forced filtered dilution air into the chamber. The stainless steel inlet for the engine emissions and dilution air stretched across the base of the chamber and contained outlet holes of varying diameters to dissipate and mix the exhaust in the chamber. A stainless steel gridded plate rested above the inlet to further enhance mixing and assist in providing a uniform mix of diesel exhaust in the chamber.

Three filter holder pipes were inserted into the chamber equidistant from each other to hold the respirator filter samples (Sample Ports A and B) with the third filter holder for the Pre Filter sample. These were connected to vacuum pumps to draw the diesel and dilution air mixture through the sampling ports. Flow rate was measured using the Alnor Air Velocity Meter Model 9870. Dry and wet bulb temperature were measured using a calibrated Zeal whirling hygrometer, with relative humidity determined using a psychometric chart. Sample ports at each position allowed sampling of EC by NIOSH 5040, and PNC using the EEPS.

Diesel emissions were drawn through the respirator filter by constant flow vacuum pumps. Following discussion with the manufacturers, a flow rate of 170L/min through the filter was selected as being broadly representative of the PAPRs general operating conditions.

Six replicate tests were conducted, for each of the filters. Sampling occurred over a one hour period which was consistent with previous studies (Burton et al, 2014-2017) however this time is considered to be much less than the time a worker may reasonably use a PAPR in a workplace environment.

PNC was recorded every 30 minutes over the one hour sampling period.

The sampling configuration is shown in Figures 3.1, 3.2 and 3.3.

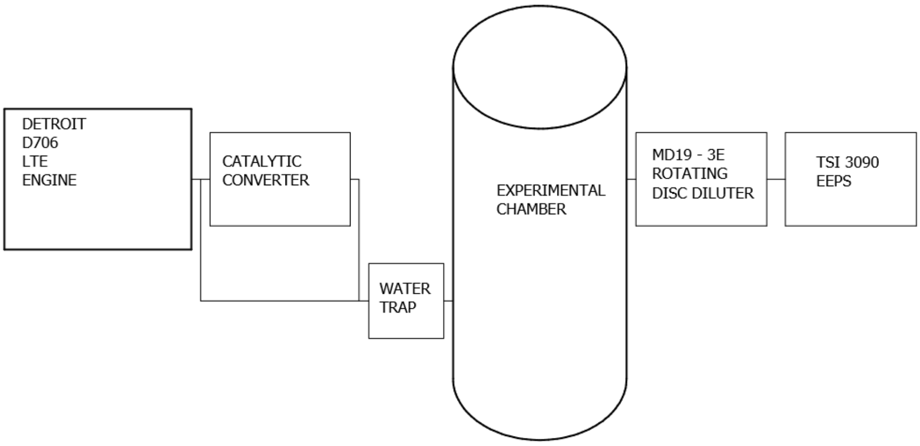

Figure 3.1 Project Design

Figure 3.2 Sampling Configuration

Figure 3.3 Example of custom made adapter to mount filter inside the Experimental Chamber

3.6 Method Validation

3.6.1 Testing without filter in place

The setup was tested at the beginning of each sampling period prior to any samples being collected by comparing the pre filter and Port A and Port B PNC, without a respirator filter in place. This was to confirm that all sampling lines were giving comparable results. Samples were collected without respirator filters in place; and analysed for EC, TC and PNC. This confirmed that there was no sampling bias from the experimental set up.

3.6.2 Zero scan at start of day

A zero scan with fresh air was conducted at the commencement of each sampling day to confirm that there was no residual contamination of the chamber or the EEPS.

3.7 Penetration Testing by External Laboratory

To enable comparison of the results from this study to the results obtained from penetration testing using the standards specified protocol, the three filter models were sent to BSI, a UK based laboratory which performs filter penetration testing. The aim was to test the filters using the challenge aerosol NaCl as specified in AS1716 (Standards Australia International Ltd and Standards New Zealand, 2012) and Paraffin Oil which is specified as an alternative to NaCl in AS ISO16900.3 and EN143/EN149 (Standards Australia Limited, 2015, CEN, 2001, CEN, 2000).

3.8 Outcome Parameters and data treatment

The airborne concentration of EC and TC were calculated using the recorded time and flow rate, as well as the analytical results from the equation (NIOSH, 2016):

$$Concentration\ (mg/m^3) = \frac{W - W_b}{V}$$

Where W (µg) = mass of elemental carbon on the filter for elemental carbon

= mass of elemental carbon + organic carbon on the filter for total carbon

W_b (µg) = average mass on blank filters

Volume (L) = Sampling time (minutes) multiplied by sampling flow rate (L/min), corrected to Standard Temperature and Pressure.

Mean Sea Level Pressure was obtained from the Bureau of Meteorology website http://www.bom.gov.au/climate/dwo/IDCJDW2001.latest.shtml for Albion Park, the closest operating weather station. The result for 9am and 3pm were averaged for each sampling date. This data was used to correct for Standard Temperature and pressure.

Particle number count was recorded every second and the results for each measurement position averaged over a 2 minute period, after the initial 30 seconds of data post switching was removed. Penetration by PNC using the average result for each time period was also calculated.

3.8.1 Treatment of Results at or Below the Limit of Detection

Several EC results were below the detection limit for the method and for some the total weight was less than zero after subtracting the blank result. These results were substituted with a value of 0.85µg, being half of the limit of detection (NIOSH, 2016). Given the low number of samples in the study, this substitution method was considered to represent those sampling results most appropriately for the purposes of this study (Bullock et al., 2006).

Particle count data was corrected so that any values below the LOD ([EEPS Manual, Figure 1 plot of detection levels) for their size were replaced with half the LOD. Total particle count (summation over all sizes) and percentage penetration were calculated from the corrected data.

3.8.2 Data Analysis

3.8.2.1. Management of Data

Microsoft Excel 2013 (Microsoft Corporation) was used to collate the data obtained and calculate the airborne concentrations and percentage penetration. Data was reviewed for any errors or inconsistencies in this format. SPSS Statistics Version 24 (IBM) was used for further analysis of the data.

3.8.2.2. Statistical analysis

Box plots were utilised to identify outliers within the tabulated data, which were reviewed to check for errors in data entry or processing. These identified outliers were subsequently determined to be valid and as such were used in further data analysis. Descriptive statistics were used to summarise the sampling data.

Data was compared using Q-Q plots and the Shapiro Wilks test ($p > 0.05$) with these normality tests showing the data as most consistent with a normal distribution. The mean and 95% Upper Confidence Level (*UCL*) were used to determine whether the hypotheses were accepted. A significance level of $p < 0.05$ applied for all statistical tests.

4 RESULTS

Respirator filter evaluation was conducted at E.R.P. Engineering Pty Ltd between the 18th October and the 23rd November 2017, using filters supplied by each manufacturer.

Two sample ports were utilised for the testing, six replicates of each filter were evaluated and filters were randomly allocated with the exception that no two filters of from the one manufacturer were tested together.

4.1 Temperature and Humidity

The temperature averaged 25.9°C within the experimental chamber ($SD = 1.6$ n=26). Relative Humidity averaged 55.5% within the experimental chamber ($SD = 8.7$ n=26).

4.2 Pre filter EC Concentration

The target EC concentration in the experimental chamber was 1mg/m^3 which is ten times the exposure limit and indicative of airborne concentrations encountered in poorly controlled working environments. The EC pre filter in this study averaged 1.04 mg/m^3 (SD = 0.3, n = 26).

4.3 Visual Observations

The samples were inspected and compared prior to analysis. The majority of the samples had minimal to slight discolouration of the filters.

4.4 EC/TC ratio

The ratio of elemental carbon to total carbon is reported in a number of studies and can be used to compare engine operating conditions. In this study, the mean EC/TC ratio was 0.69 (SD=0.05, n=26).

4.5 Penetration Test Results

4.5.1 EC Penetration

Table 4.1 gives summary information for EC penetration and Table 4.1 and Figure 4.1 shows %EC penetration by filter. All filters failed to meet their rated % filtering efficiency when evaluated for EC.

Table 4.1 Elemental Carbon penetration summary

Filter Model	AS/NZS Rating	Acceptable % Penetration	Median % EC Penetration	95% CI Upper
060-23-11PAUS	PAPR-P2	1.00%	1.69	2.00
AR HE-F001	PAPR-P3	0.05%	0.10	0.11
PAF-0037	PAPR-P3	0.05%	0.13	0.18

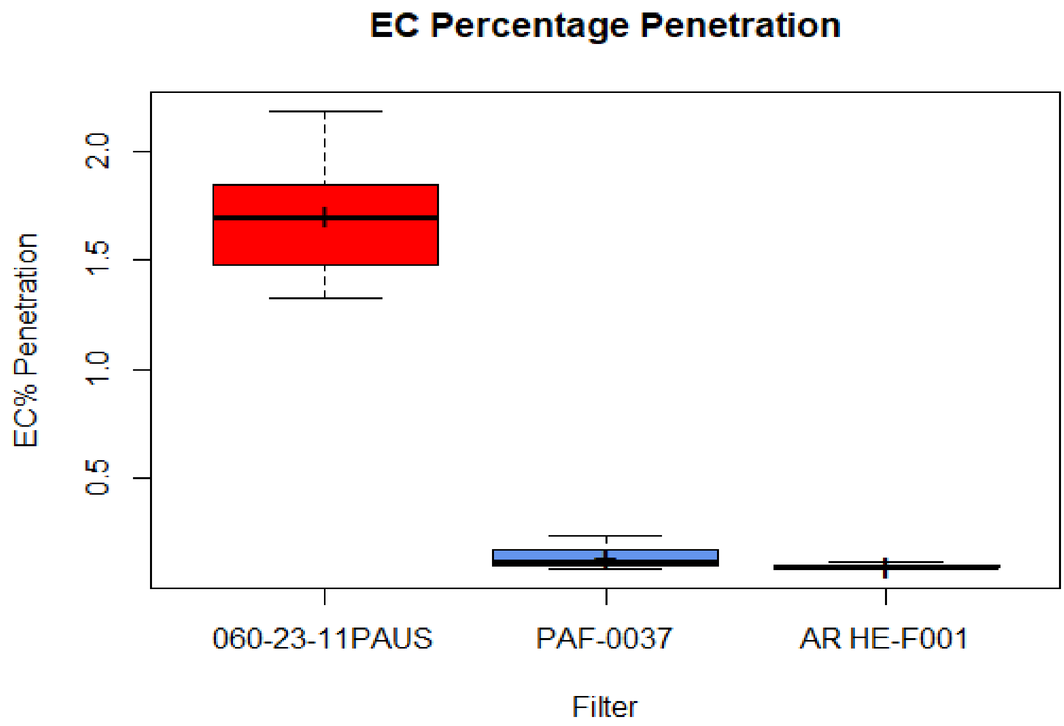

Figure 4.1 Elemental Carbon % Penetration by filter model

4.5.2 TC Penetration

Table 4.2 gives summary information for TC penetration and Figure 4.4 shows %TC penetration by filter. All filters failed to meet their rated % filtering efficiency when evaluated for TC.

Table 4.2 Total Carbon % penetration summary

Filter Model	AS/NZS Rating	Acceptable % Penetration	Median % TC Penetration	95% CI Upper
060-23-11PAUS	PAPR-P2	1.00%	2.71	3.85
AR HE-F001	PAPR-P3	0.05%	6.14	7.06
PAF-0037	PAPR-P3	0.05%	7.08	8.41

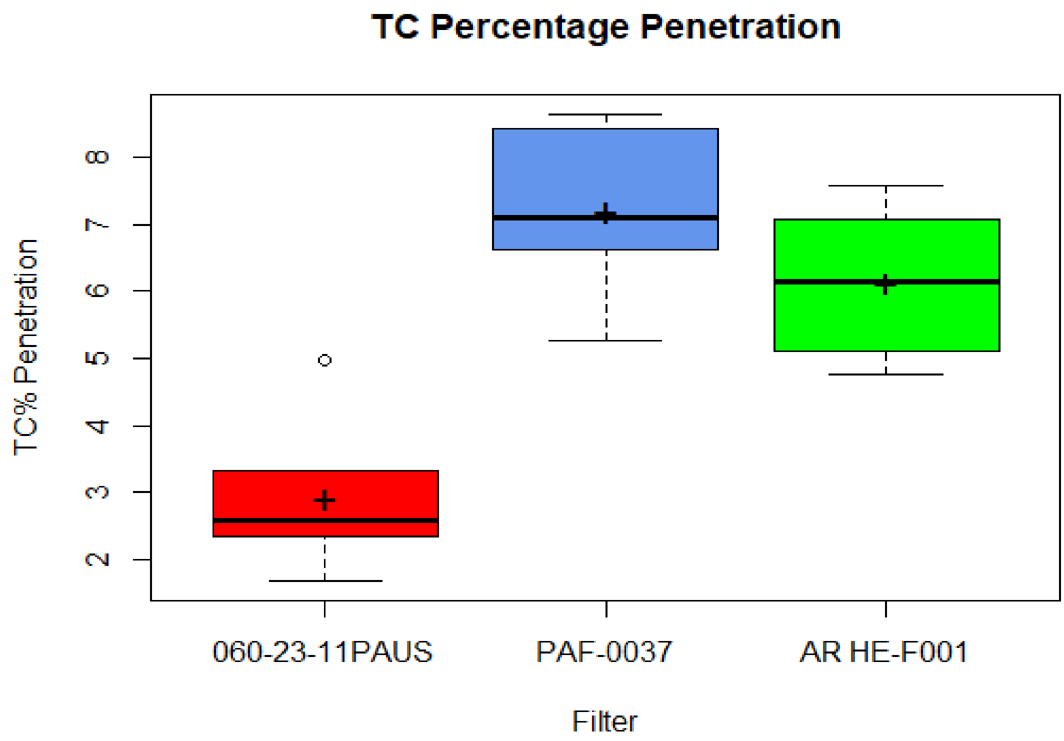

Figure 4.2 Total Carbon % Penetration by filter model

4.5.3 Particle Number Count (PNC) Penetration

PNC was measured at the commencement of the test, at 30 minutes and at the end of the test, at 60 minutes. Table 4.3 gives summary information for TC penetration.

Table 4.3 PNC penetration summary

Filter Model	AS/NZS Rating	Acceptable % Penetration	Median % PNC Penetration	95% CI Upper
060-23-11PAUS	PAPR-P2	1.00%	2.85	4.58
AR HE-F001	PAPR-P3	0.05%	3.43	5.25
PAF-0037	PAPR-P3	0.05%	3.52	5.25

Figures 4.3-4.7 show the %Penetration by PNC in the 25nm-530nm range. All filters failed to meet their rated filtering efficiency when evaluated for PNC penetration.

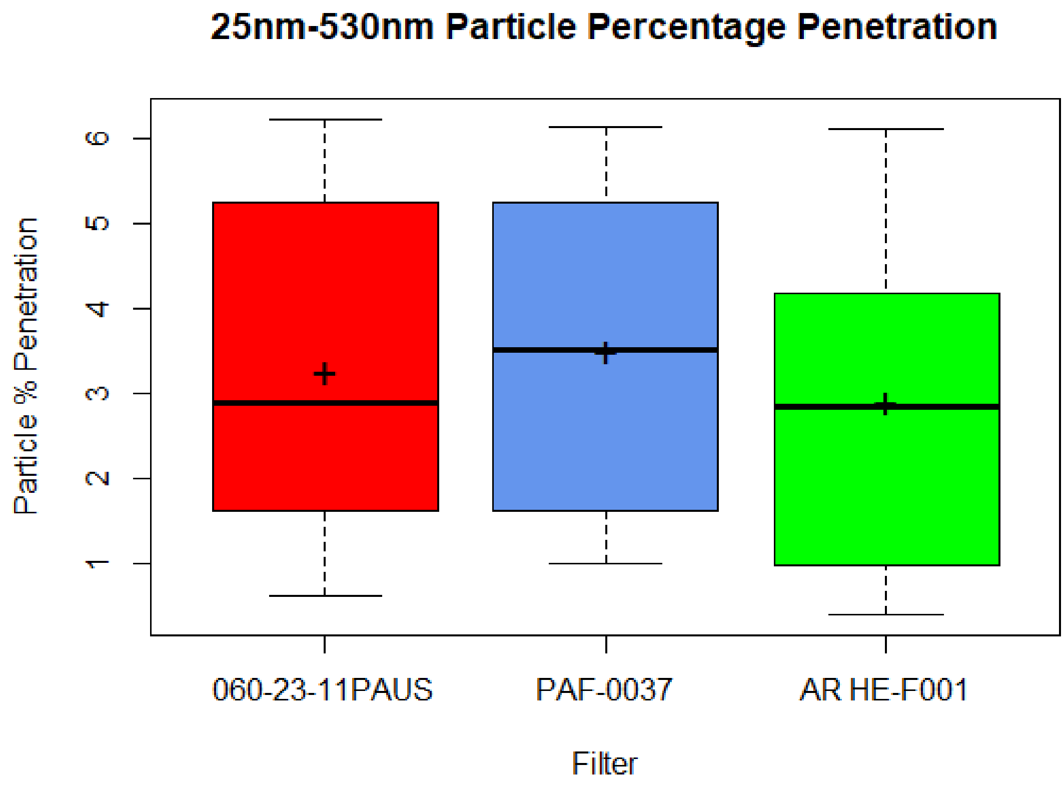

Figure 4.3 Particle Number % Penetration 25-530nm by filter model

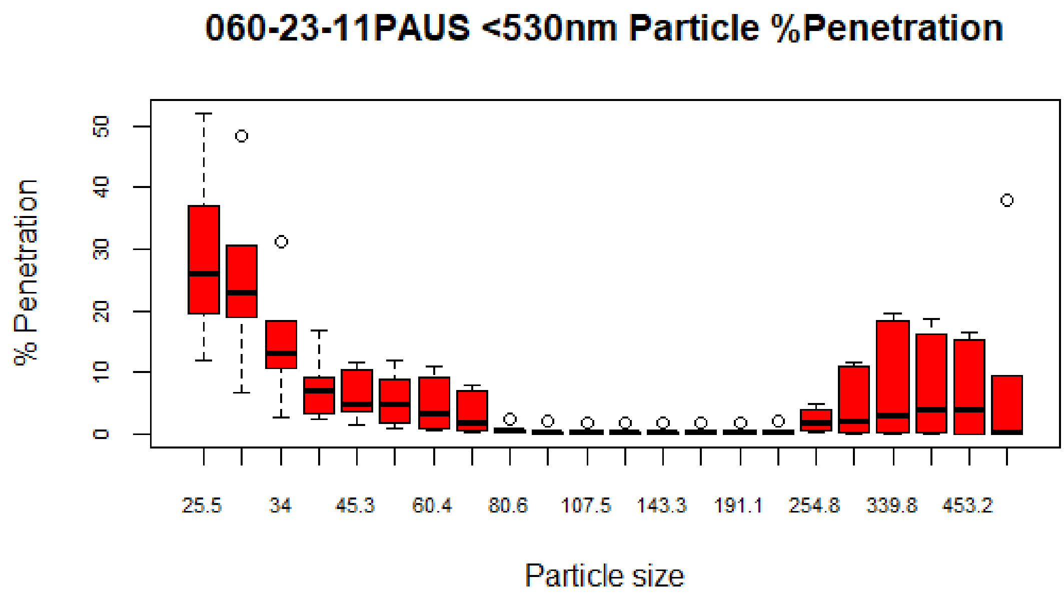

Figure 4.4: Particle Number %Penetration 25-530nm 060-23-11PAUS

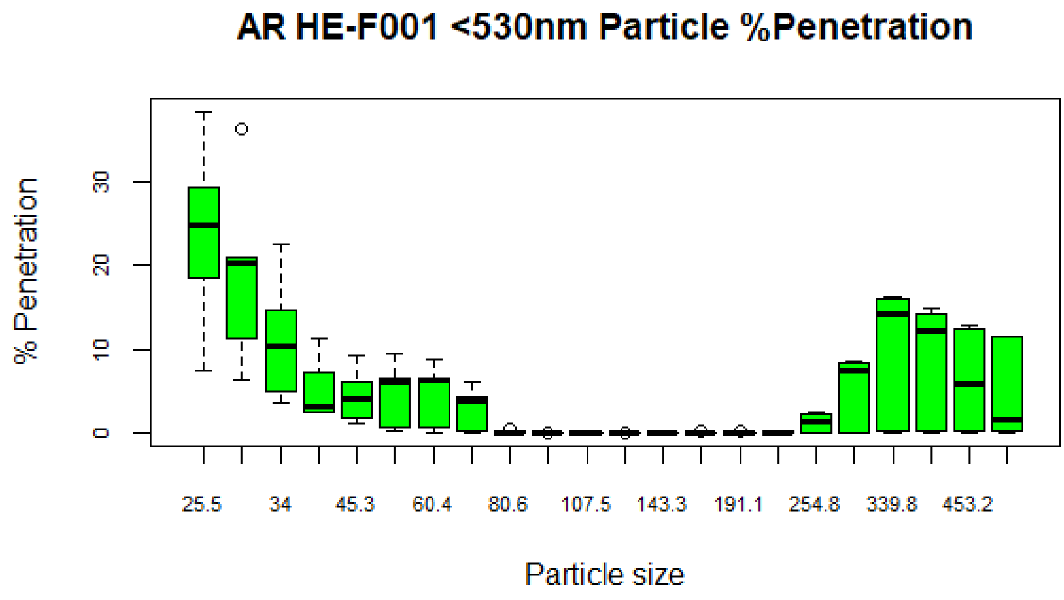

Figure 4.5 Particle Number %Penetration 25-530nm AR HE-F001

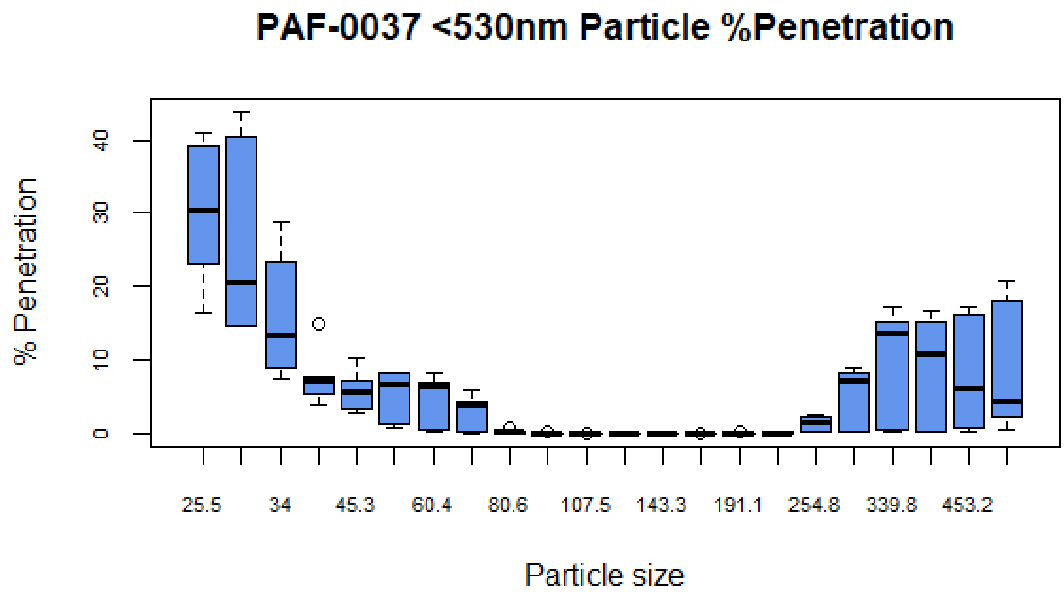

Figure 4.6 Particle Number % Penetration 25-530nm PAF-0037

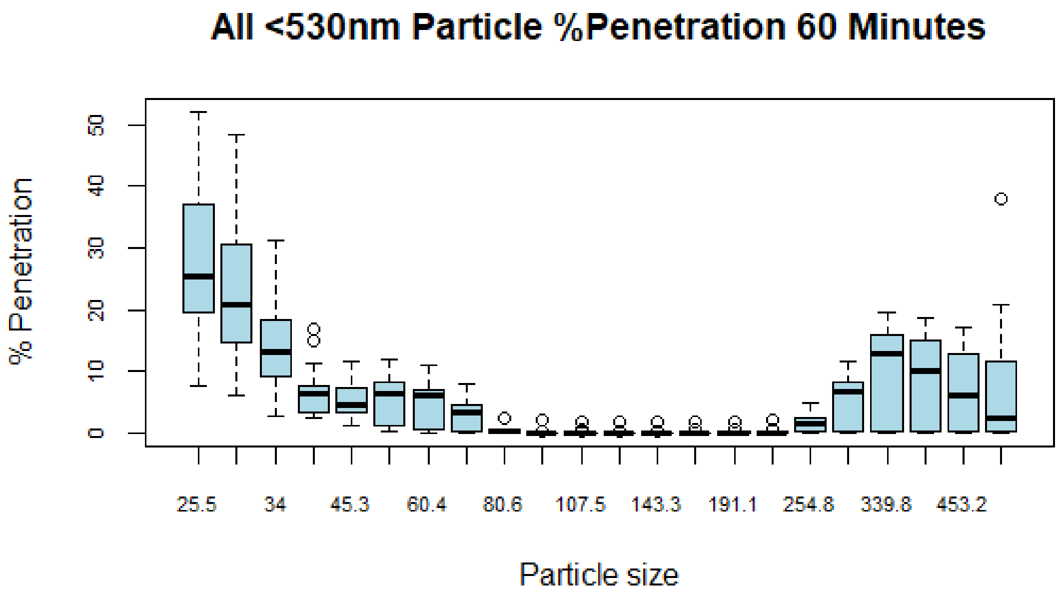

Figure 4.7 Particle Number %Penetration 25-530nm All Filters

On the basis of the varying % penetration across the different size ranges observed in Figures 4.5-4.8, an additional set of analysis was done to examine the performance in these regions. First, the data was separated into three size range "buckets" based on particle midpoint diameters:

A = 25.5 to 69.8nm,

B = 80.6 to 220.7nm, and

C = 254.8 to 523.2nm.

Figure 4.8 shows the box plots of PNC % penetration for the collapsed buckets.

For additional detail, Figure 4.10 shows the filter performance in the central 80.6-220.7nm bucket. The 060-23-11PAUS filter meets its specified threshold of 1% penetration for particles in this region, although it does not do this for particles outside this range.

It is more difficult to say whether the other two filters, PAF-0037 and AR HE-F001, have average performance below their required threshold of 0.05% penetration in this range; but as they failed to meet the required filtration efficiency in every other evaluation, further testing was not done.

UNIVERSITY OF WOLLONGONG AUSTRALIA

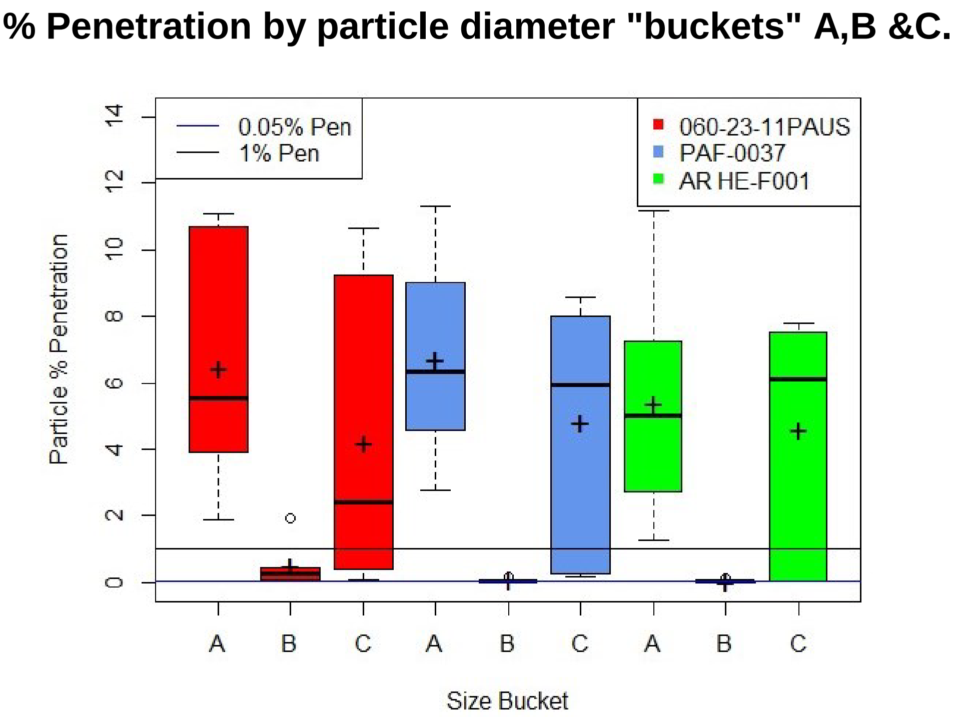

Figure 4.8 PNC % Penetration for the collapsed buckets; A = 25.5 to 69.8nm, B = 80.6 to 220.7nm, and C = 254.8 to 523.2nm.

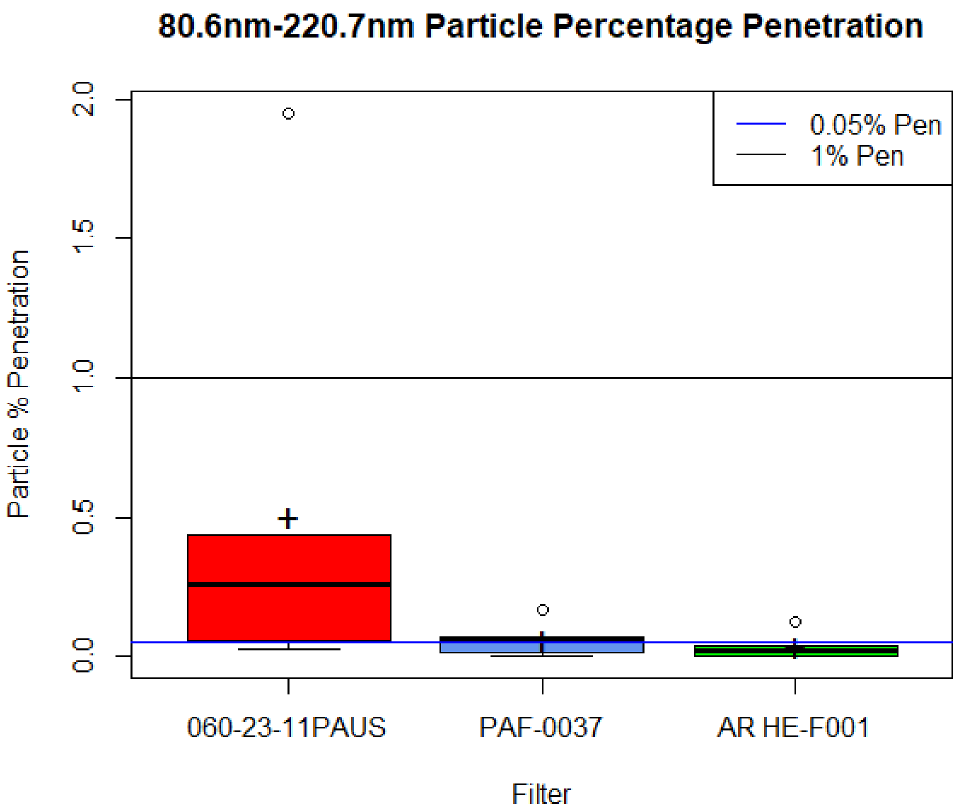

Figure 4.9 PNC % Penetration for the 80.6-220.7nm size range

Analysis of the different groupings of size ranges demonstrates that all of the filters are more efficient at the 80.6-220.7 particle size range. However, all filters failed to meet their rated %penetration for the particle size ranges on either side and overall.

4.5.4 Effect of Exposure Time on Particle Number Count Penetration through the Respirator Filters

To evaluate the effect of increased wear time on particle penetration, PNC was recorded at 0, 30 and 60 minutes during the sampling period. Figure 4:11 plots the performance at the different points in time as a stacked bar chart for each particle size fraction. There was no significant difference in the median percentage penetration between the time points.

The conclusion is that filtering efficiency and the profile of the penetrating particles remained constant across the test period.

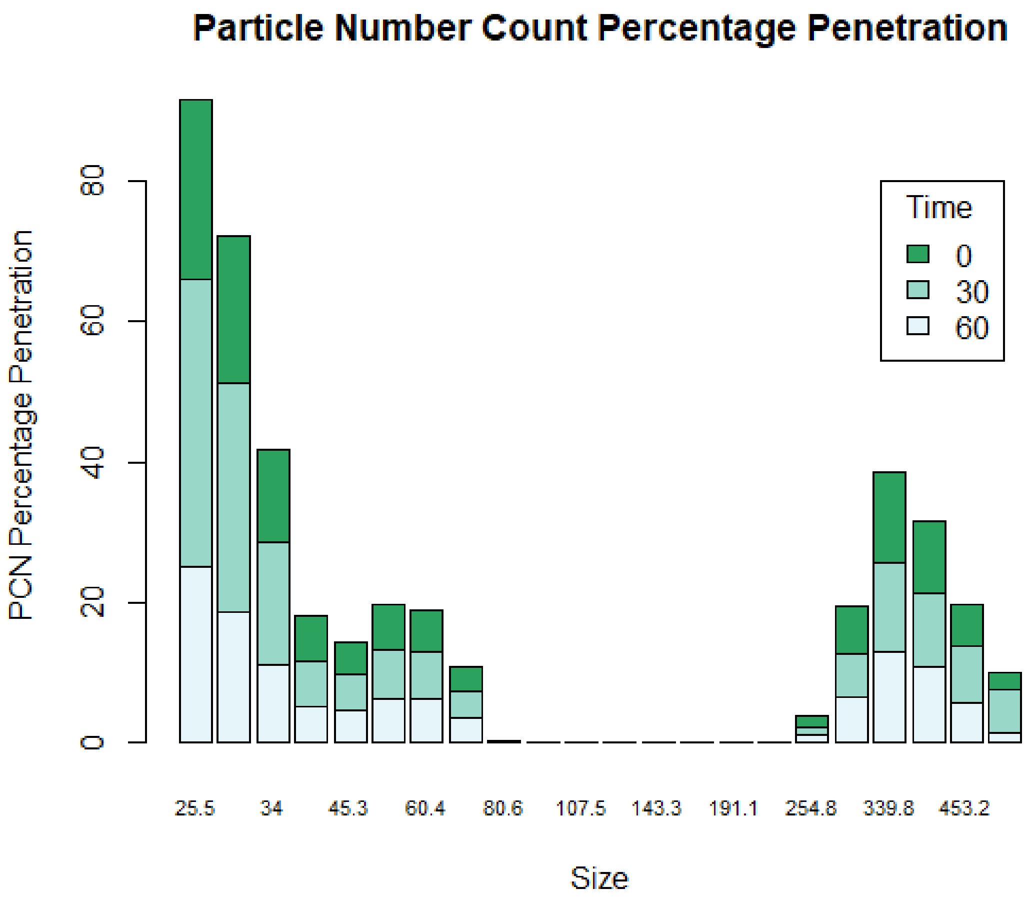

Figure 4.10 Effect of exposure time on % Particle Number Count

UNIVERSITY OF WOLLONGONG AUSTRALIA

4.6 Results of Filter Testing by External Laboratory

Four samples of each filter model were sent to an external laboratory using BS EN 13274-7:2008 to enable comparison of the results obtained from testing with ISO standards specified challenge aerosols (Sodium Chloride and Paraffin) with the findings of DPM penetration in this study. The results are reported in Table 4.4. For consistency across all tests, a flow rate of 170 L/min was chosen.

Table 4.4 Challenge Aerosols %Penetration by filter model

Filter Model	Median %Pen NaCl	Std. Dev	Median %Pen Paraffin	Std. Dev
AR HE-F001	0.004	0.0005	0.007	0.0012
PAF-0037	0.005	0.0011	0.006	0.0013
060-23-11PAUS	1.790	0.088	7.250	0.289

A paired sample t-test evaluating the effect of challenge aerosol, showed the AR-HH-F001 and the 060-23-11PAUS performed significantly differently ($p<0.05$) in filtration efficiency between NaCl and Paraffin tests. The PAF-0037 filter did not perform significantly differently between the aerosol tests ($p=0.2$).

The comparison for these results and challenge aerosols for all filters is displayed in Table 4.5 and Figures 4.11-13.

Table 4.5 Comparison of challenge agents

Median %Penetration	060-23-PAUS	PAF-0037	AR HE-F001
EC %	1.69	0.130	0.100
TC %	2.71	7.080	6.140
PNC %	3.43	3.520	2.850
NaCl %	1.79	0.005	0.004
Paraffin %	7.25	0.006	0.007

UNIVERSITY OF WOLLONGONG AUSTRALIA

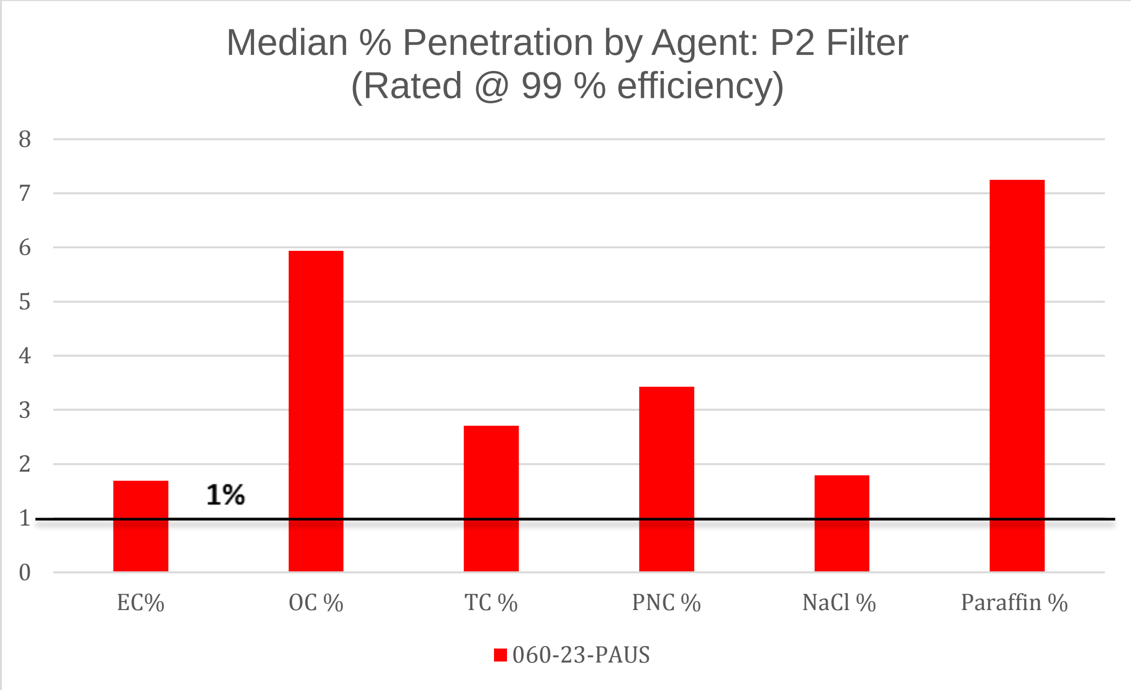

Figure 4.11 060-23-PAUS (P2) % Penetration of different challenge agents.

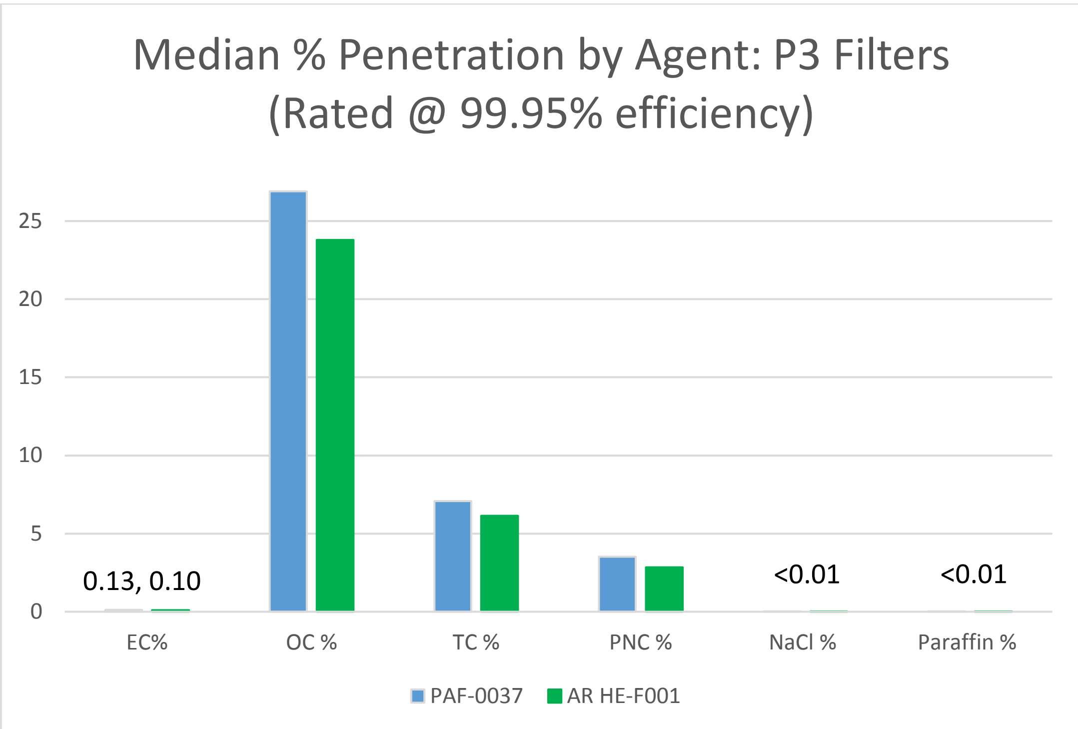

Figure 4.12 PAF-0037 & AR-HE-F001 (P3) % Penetration of different challenge agents.

The filters were then grouped together and NaCl and Paraffin penetration was compared for "AllFilters" (Table 4.6) with the result that the overall means were significantly different with Paraffin Oil being the more conservative challenge aerosol. Figure 4.13 illustrates the effect of different challenge aerosols on penetration results depicting the Mean ± 95% Confidence Interval, n = 4, Paraffin Oil and NaCl were tested by the external laboratory, EC, TC and PNC were tested during the study.

Table 4.6 All filters Comparisons

All Filters	Mean	Std. Dev	N	Sig. (2tailed)
%Pen NaCl	0.586	0.861	12	0.038
%Pen Paraffin	2.420	3.57	12	0.039

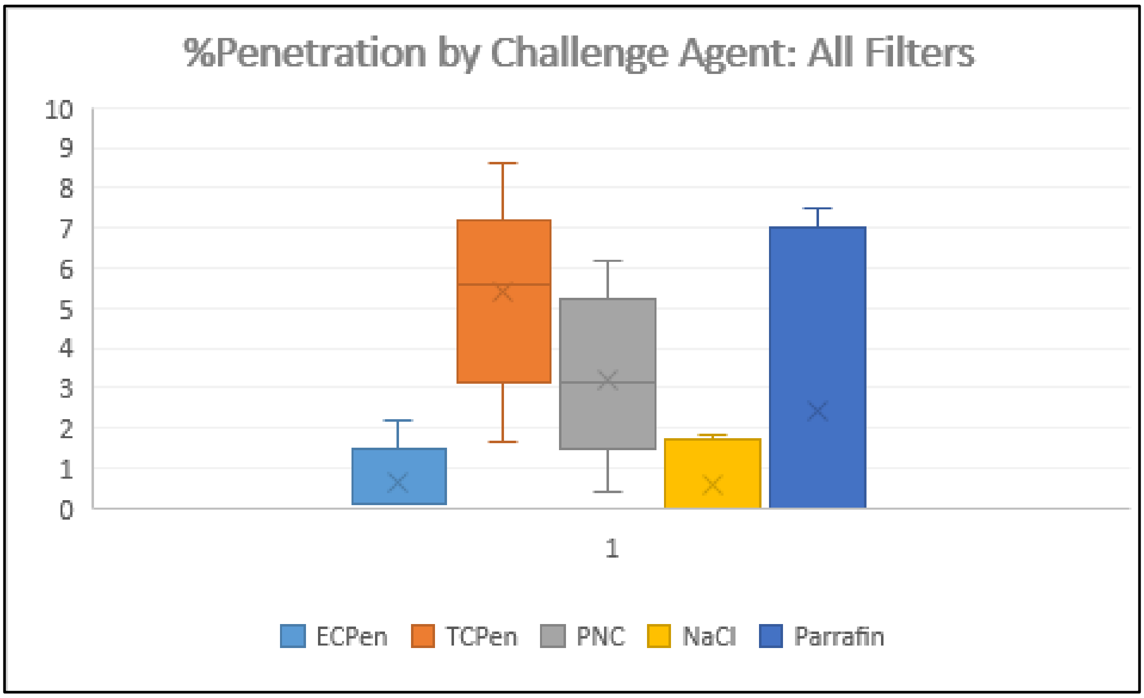

Figure 4.13 Effect of Challenge Aerosol on %Penetration Results.

5 DISCUSSION AND CONCLUSION

These studies raise concerns regarding the adequacy of the AS1716:2012 sodium chloride penetration test for respiratory protection commonly provided against DPM. The study results indicate a penetration of EC & TC and ultrafine particles through these PAPR filters in excess of their Australian Standard particulate filtration efficiency ratings.

It has been postulated that ultrafine particles may contribute to adverse cardiovascular mortality and morbidity associated with diesel engine emissions (Martinelli, Olivieri & Girelli 2013) and the absence of an occupational exposure standard with respect to particle number for these small diameter particles creates challenges in determining the appropriate level of control measures to mitigate health impacts on workers.

5.1 Key Findings

5.1.1 DPM Penetration at Standard Designated Flow Rate

Research Question 1: Do standards certified PAPR filters used in Australian workplaces effectively filter out DPM, when challenged with emissions from a diesel engine and measured as penetration of EC, TC and PNC through the respirator filter media?

Findings: All filters failed to meet their rated % filtering efficiency when evaluated for EC, and TC. All filters failed to meet their rated filtering efficiency when evaluated for %Penetration by PNC in the 25nm-530nm range.

5.1.2 Most Penetrating Particle Size

Research Question 2: Determine the Most Penetrating Particle Size range (MPPS) through these PAPR filters.

Analysis of the different groupings of size ranges (figure 4.9) demonstrates that all of the filters are more efficient at the 80.6-220.7 particle size range. However, all filters failed to meet their rated %penetration for the particle size ranges on either side (25-80nm & 220-530nm), and overall.

5.1.3 Comparison of Test Methods

Research Question 3: Do current sodium chloride (NaCl) penetration test requirements as per AS / NZS 1716 Section 4.3.5 Appendix I and Paraffin oil penetration test requirements in recently adopted AS ISO 16900.3 (Standards Australia Limited, 2015) adequately assess whether standards certified PAPR filters effectively filter out DPM?

Findings: Two of the three filters performed significantly differently with the two challenge aerosols ($p<0.05$), and the mean %penetration was higher for Paraffin for all three filters. When AllFilters were considered together, there was a significant difference in penetration between the two tests, with the Paraffin test yielding a four times higher penetration than the NaCl test.

Therefore, results from external laboratory testing using standard challenge aerosols show that Paraffin Oil is a more conservative test than NaCl and closer to DPM penetration. Similarly, PNC penetration after 60 minutes exposure time is more conservative than EC penetration.

The 60 minutes of exposure time measured in this study is well within a realistic time frame that a worker may wear a single use negative pressure respirator filter without replacement, however a PAPR wearer may utilise the same filter for multiple days. This study selected the same timeframe (ie 60 minutes) for consistency with previously published studies (Burton et al., 2016).

Current Standards Australia penetration tests are conducted over a much shorter time-period and therefore may not adequately assess whether the respirator is effective for the wear time of the worker.

This potential limitation with the Standards Australia test protocol could be addressed by adopting the ISO Standards currently being developed and stipulating the Paraffin penetration test as well as NaCl. However, at present there is limited research to confirm that the test protocols specified in the ISO standard will ensure certified filters effectively protect workers from inhaling DPM.

5.2 Study Implications

The research findings identify potential shortcomings in the current Standards Australia test protocols for evaluation of filtering efficiency against DPM. This has implications for workers and employers who rely on Standards certified filters to prevent exposure to diesel engine emissions. Furthermore, data from the literature review suggest that certification testing is not conducted at flow rates representative of moderate to heavy work, with previous experimental findings indicating that ingress of particles may increase at the higher work rates.

The implication that the current test methodology has some limitations has been acknowledged by Standards Australia in the preface to AS/NZS 1716. The fact that international test criteria distinguish between oil and non-oil based substances should not be ignored by Australian manufacturers and suppliers, especially when published research supports the findings that filter penetration may differ when challenged with DPM (Janssen, 2003, Burton et al., 2016). Given the current work to develop aligned International Standards it is important that these standards adequately ensure protection against hazardous contaminants such as DPM, by utilising test protocols that are representative of the hazardous contaminants and consistent with worker respirator usage. It should be noted that the draft ISO standards specify NaCl or Paraffin Oil as a challenge aerosol, but do not specify under what scenarios each one should be used. They do however, require selection of an appropriate respirator with consideration of work rate. Although limited to one respirator filter model, the results of this study would indicate that Paraffin Oil would provide a more conservative estimate of exposure to DPM than NaCl and hence be more protective of worker health.

5.3 Conclusion

This research suggests that limitations in the current test protocols for filtering efficiency specified in AS/NZS 1716, may mean workers are not adequately protected against DPM, under all circumstances of diesel generated particles.

This research will assist the development of improved Australian and International standards relating to the selection and evaluation of DPM respiratory protection, so as to better manage the health risk for personnel exposed to this workplace carcinogen.

5.4 Recommendations

These findings should be considered when determining whether the ISO standards currently being drafted, which incorporate alternative challenge aerosols and work rates, should be adopted in Australia. In particular it is recommended to mandate the use of Paraffin Oil as the challenge aerosol, given this was a more conservative measure in this study (than the alternative challenge agent NaCl), and is consistent with ISO standards and European rating schemes. The findings of this study will inform users of the limitations in selection of respiratory protection and contribute to manufacturers and suppliers knowledge in the recommendation of PAPRs for use against DPM.

In the interim, end users should confirm with their supplier that the filters recommended for use against DPM have undergone testing with a more conservative challenge aerosol. Given the high Organic Carbon penetration (Figs 4.11 & 4.12), consideration should also be given to selecting filters with some capacity to remove organic vapours.

5.5 Acknowledgements:

We would like to acknowledge ERP Engineering Ltd for their assistance with the Diesel Engine and EEPS, Jennifer Hines of EHS Solutions for Research Assistance with data collection, BSI UK for filter penetration testing and Theresa O'Brien for assistance with the statistical analysis.

We also appreciate the open engagement with, and support from respirator manufacturers 3M Australia, Dräger Pacific and Clean Space Technology.

This research has been conducted with the support of the University of Wollongong and Coal Services Health and Safety Trust.

6 REFERENCES

3M Racal Airstream Available: https://www.3m.com.au/3M/en_AU/company-au/all-3m-products/~/3M-Airstream-Main-Filter-P2-Heavy-Duty-060-23-04P/?N=5002385+3293696149&preselect=8695925+8709322+8711405+8720539+8720547+8720771+3293786499&rt=rud [Accessed 24/9/2018

ACARP Research Funding; https://www.acarp.com.au/funding.aspx accessed 21st September 2018.

AIOH 2017, *Diesel Particulate Matter and Occupational Health Issues,* Australian Institute of Occupational Hygienists, Avaiable: <https://www.aioh.org.au/resources/position-papers-3>.[Accessed 24/9/2018

ALFÖLDY, B., GIECHASKIEL, B., HOFMANN, W. & DROSSINOS, Y. 2009. Size-distribution dependent lung deposition of diesel exhaust particles. *Journal of Aerosol Science,* 40**,** 652-663.

BAKAND, S., HAYES, A. & DECHSAKULTHORN, F. 2012. Nanoparticles: a review of particle toxicology following inhalation exposure. *Inhalation Toxicology,* 24**,** 125-135.

BIRCH, M. E. & CARY, R. A. 1996. Elemental Carbon-Based Method for Monitoring Occupational Exposures to Particulate Diesel Exhaust. *Aerosol Science and Technology,* 25**,** 221-241.

BORM, P., KLAESSIG, F. C., LANDRY, T. D., MOUDGIL, B., PAULUHN, J. R., THOMAS, K., TROTTIER, R. & WOOD, S. 2006. Research Strategies for Safety Evaluation of Nanomaterials, Part V: Role of Dissolution in Biological Fate and Effects of Nanoscale Particles. *Toxicological Sciences,* 90**,** 23-32.

British Standards Institution 2008 BS EN 13274-7:2008: Respiratory protective devices. Methods of test. Determination of particle filter penetration.

BROOK, R., MITTLEMAN, M., PETERS, A., SISCOVICK, D., SMITH JR, S., WHITSEL, L., KAUFMAN, J., RAJAGOPALAN, S., ARDEN POPE III, C., BROOK, J. R., BHATNAGAR, A., DIEZ-ROUX, A., HOLGUIN, F., HONG, Y. & LUEPKER, R. 2010. Particulate Matter Air Pollution and Cardiovascular Disease: An Update to the Scientific Statement from the American Heart Association. *Circulation,* 121**,** 2331-2378.

BULLOCK, W. H., IGNACIO, J. S. & AMERICAN INDUSTRIAL HYGIENE ASSOCIATION EXPOSURE ASSESSMENT STRATEGIES COMMITTEE 2006. *A strategy for assessing and managing occupational exposures,* Fairfax, VA, AIHA Press, American Industrial Hygiene Association.

BUNN, W. B., VALBERG, P., SLAVIN, T. & LAPIN, C. 2002. What is new in diesel. *International Archives of Occupational and Environmental Health,* 75**,** 122-132.

Burton, K., Davies, B., Jones, A. & Whitelaw, J. (2017). Respiratory Protection against Ultrafine Diesel Particulate. AIHce2017 Seattle, Washington.

BURTON, K. A., WHITELAW, J. L., JONES, A. L. & DAVIES, B. 2016. Efficiency of Respirator Filter Media against Diesel Particulate Matter: A Comparison Study Using Two Diesel Particulate Sources. *Ann Occup Hyg,* 60**,** 771-9.

Burton, KA, Whitelaw, JL, Jones, AL & Davies, B 2016 "Respiratory Protection – Are our Standards Protecting Worker Health or Providing a False Sense of Security? CSHST 20634 Final Report" Available: https://www.coalservices.com.au/mining/about-us/health-safety-trust/recently-completed-projects/ Accessed 15/10/2018.

CEN 2000. EN143:2000: Respiratory Protective Devices - Particle Filters - Requirements, testing, marking. Brussels, Belgium: European Committee for Standardization. SAI Global Limited

CEN 2001. EN149:2001: Respiratory Protective Devices - Filtering half masks to protect against particles - Requirements, testing, marking. Brussels, Belgium: European Committee for Standardization. SAI Global Limited

CHERRIE, J. W. 2009. Reducing occupational exposure to chemical carcinogens. *Occupational Medicine,* 59**,** 96-100.

CleanSpace Technology 2018, Available: https://cleanspacetechnology.com/wp-content/uploads/2016/09/PAF-0037-CleanSpace-Hi-Cap-P3-TM3-Filter_Data-Sheet-ENG-4.pdf [Accessed 24/9/2018

CHO, H.-W., YOON, C.-S., LEE, J.-H., LEE, S.-J., VINER, A. & JOHNSON, E. W. 2011. Comparison of pressure drop and filtration efficiency of particulate respirators using welding fumes and sodium chloride. *The Annals Of Occupational Hygiene,* 55**,** 666-680.

CODE OF FEDERAL REGULATIONS 1995. Title 42 Part 84 Approval of Respiratory Protective Devices. Washington, DC: US Government Printing Office.

Davies, B 2013, *Coal Services Health and Safety Trust Research Project, Calibration of Portable Raw Exhaust Diesel Particulate Analysers*, University of Wollongong.

DAVIES, B. & ROGERS, A. 2004. *A Guideline for the Evaluation and Control of Diesel Particulate in the Occupational Environment,* Tullamarine, Victoria, Australian Institute of Occupational Hygienists.

Defence Work Health and Safety 2012, *Defence WHS Fact Sheet No 27 – October 2012 Long-Term Exposure to Diesel Exhaust Emissions*, Avaialble: http://www.peacekeepers.asn.au/newsitems/2012/Diesel%20Fact%20Sheet%20Oct.pdf [Accessed 24/9/2018

DEPARTMENT OF MINES AND PETROLEUM 2013. Management of diesel emissions in Western Australian mining operations - guideline. Western Australia: Resources Safety, Department of Mines and Petroleum.

DEPARTMENT OF NATURAL RESOURCES AND MINES 2012. Shift adjustment of the guideline limit for diesel particulate matter, Safety Bulletin No 127. Queensland, Australia: Queensland Government.

DIESELNET. 2016. *Emission Standards* [Online]. Available: http://www.dieselnet.com/standards [Accessed23/10/2018.

Dräger Safety Pacific Pty Ltd 2011, *Diesel Particulate Matter*, Australia.

Dräger Safety Pacific Pty Ltd [Online]. Available: https://www.draeger.com/en_aunz/Applications/Products/Personal-Protection-Equipment/Powered-Air-Purifying-Respirators/X-plore-8000 [Accessed 23/10/2018.

HAGHIGHAT, F., BAHLOUL, A., LARA, J., MOSTOFI, R. & MAHDAVI, A. 2012. Development of a Procedure to Measure the Effectiveness of N95 Respirator Filters Against Nanoparticle Report R-754. Montreal, Quebec: IRRST.

HESTERBERG, T. W., LONG, C. M., SAX, S. N., LAPIN, C. A., MCCLELLAN, R. O., BUNN, W. B. & VALBERG, P. A. 2011. Particulate Matter in New Technology Diesel Exhaust (NTDE) is Quantitatively and Qualitatively Very Different from that Found in Traditional Diesel Exhaust (TDE). *Journal of the Air & Waste Management Association*, 61**,** 894-913.

IFA. 2016. *GESTIS International Limit Values* [Online]. Available: http://limitvalue.ifa.dguv.de [Accessed 23/10/2018.

ISO 2016. Respiratory protective devices - Selection, use and maintenance - Part 1: Establishing and implementing a respiratory protective device programme. Switzerland: International Standard. SAI Global Limited

JANSSEN, L. 2003. Principles of physiology and respirator performance. *Occupational Health and Safety,* 72**,** 73 - 76.

JANSSEN, L. & BIDWELL, J. 2006. Performance of Four Class 95 Electret Filters Against Diesel Particulate Matter. *Journal of the International Society for Respiratory Protection,* 23**,** 21-29.

KASPER, M. 2004. The Number Concentration of Non-Volatile Particles Design Study for an Instrument According to the PMP Recommendations. *SAE International Technical Paper Series,* 2004-01-0960.

LIU, W. K., KARPOV, E. G. & PARK, H. S. 2006. *Nano mechanics and materials: theory, multiscale methods and applications*, John Wiley & Sons.

LIUKONEN, L. R., GROGAN, J. L. & MYERS, W. 2002. Diesel particulate matter exposure to railroad train crews. *AIHA Journal,* 63**,** 610-616.

MARICQ, M. 2007. Chemical characterization of particulate emissions from diesel engines: A review. *Journal of Aerosol Science,* 38**,** 1079-1118.

MSHA 2005. Mine Safety and Health Administration Vol 70, No. 107, 30 CFR part 57 Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners. US Federal Register.

NEL, A. E., MÄDLER, L., VELEGOL, D., XIA, T., HOEK, E. M. V., SOMASUNDARAN, P., KLAESSIG, F., CASTRANOVA, V. & THOMPSON, M. 2009. Understanding biophysicochemical interactions at the nano–bio interface. *Nature Materials,* 8**,** 543.

NIOSH 2016. *NIOSH Manual of Analytical Methods (NMAM) : 5th Edition- Method Liting - D (NMAM) Method 5040 Issue 4,* Cincinnati, OH, NIOSH. Available: https://www.cdc.gov/niosh/docs/2014-151/pdfs/methods/5040.pdf [Accessed 19/12/2018

NOLL, J., GILLES, S., WU, H. W. & RUBINSTEIN, E. 2014. The Relationship between Elemental Carbon and Diesel Particulate Matter in Underground Metal/Nonmetal Mines in the United States and Coal Mines in Australia. *Journal of Occupational and Environmental Hygiene*, 205-211.

NSW DEPARTMENT OF PRIMARY INDUSTRIES 2008. Guideline for the Management of Diesel Engine Pollutants in Underground Mine Environments. Maitland, NSW: Department of Primary Industries.

NSW TRADE AND INVESTMENT MINE SAFETY 2013. Diesel Emissions in Mines.

PENCONEK, A., DRĄŻYK, P. & MOSKAL, A. 2013. Penetration of diesel exhaust particles through commercially available dust half masks. *The Annals of Occupational Hygiene,* 57, 360.

RENGASAMY, S., BERRYANN, R. & SZALAJDA, J. 2013. Nanoparticle Filtration Performance of Filtering Facepiece Respirators and Canister/cartridge Filters. *Journal of Occupational and Environmental Hygiene,* 10, 519-525.

RENN, O. & ROCO, M. C. 2006. Nanotechnology and the need for risk governance. *Journal of Nanoparticle Research,* 8, 153-191.

SAFEWORK AUSTRALIA 2016. Work Health and Safety Regulations. *In:* AUSTRALIA, S. (ed.). Commonwealth. [Online].Available: https://www.safeworkaustralia.gov.au/doc/model-work-health-and-safety-regulations [Accessed 23/10/2018.

SAFEWORK AUSTRALIA. 2016. *Hazardous Chemical Information System (HCIS)* [Online]. Available: http://hcis.safeworkaustralia.gov.au/ExposureStandards [Accessed 23/10/2018.

SILVERMAN, D. T., SAMANIC, C. M., LUBIN, J. H., BLAIR, A. E., STEWART, P. A., VERMEULEN, R., COBLE, J. B., ROTHMAN, N., SCHLEIFF, P. L., TRAVIS, W. D., ZIEGLER, R. G., WACHOLDER, S. & ATTFIELD, M. D. 2012. The Diesel Exhaust in Miners Study: A Nested Case-control Study of Lung Cancer and Diesel Exhaust. *Journal of the National Cancer Institute*, 104**,** 855-868.

STANDARDS AUSTRALIA INTERNATIONAL LTD & STANDARDS NEW ZEALAND 2009. AS/NZS 1715:2009 Selection, use and maintenance of respiratory protective equipment. Sydney / Wellington: SAI Global Ltd / Standards New Zealand.

STANDARDS AUSTRALIA INTERNATIONAL LTD & STANDARDS NEW ZEALAND 2012. AS/NZS 1716:2009 Respiratory protective devices. Sydney / Wellington: SAI Global Limited / Standards New Zealand

STANDARDS AUSTRALIA LIMITED 2015. AS ISO 16900.3:2015 Respiratory Protective Devices- Methods of test and test equipment *Part 3: Determination of particle filter penetration.* Sydney, Australia: SAI Global Limited.

STANDARDS AUSTRALIA INTERNATIONAL LTD 2015 AS ISO 16900.3:2015 Respiratory protective devices — Methods of test and test equipment — Part 3: Determination of particle filter penetration. Sydney, Australia SAI Global Limited

SWISS ASSOCIATION FOR STANDARDISATION 2014. Internal Combustion Engines - Exhaust Gas After-treatment - Particle Filter Systems - Testing Method. Winterthur: SNV Schweizerische.

WORLD HEALTH ORGANISATION 2013. Diesel and Gasoline Engine Exhausts and Some Nitroarenes. Lyon, France: International Agency for Research on Cancer.

World Health Organisation 2012, *IARC Diesel Exhaust Carcinogen Press Release #213*, International Agency for Research on Cancer.