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Respiratory Protection – Are our Standards Protecting Worker Health or Providing a False Sense of Security?

CSHST 20634
Final Report

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Executive Summary

Australian workers are exposed to emissions from diesel engines in a variety of workplaces. Diesel particulate matter (DPM) has the potential for serious health impacts to exposed workers, including lung cancer and adverse cardiovascular and irritant effects. Personal respiratory protective devices are a common control measure to mitigate worker exposure against the damaging health impacts of DPM, and to protect they need to act as effective filters.

Filtering efficiency of respiratory protection is determined by challenging filter media with specified test aerosols to calculate penetration at designated flow rates. Four specific aims were investigated in this study to determine filters certified and used in Australian workplaces effectively protect workers from exposure to emissions, and whether current protocols specified in the Australian Standard for respiratory protective devices (Standards Australia International Ltd & Standards New Zealand 2012) ensure worker health is protected.

The study was conducted in three phases. The initial phase involved developing and validating a sampling methodology, including design and construction of an experimental chamber to measure filter penetration through respirator filters, using emissions from a diesel engine as the challenge aerosol. This sampling methodology was then used to undertake the sampling program measuring penetration as a function of both mass of elemental carbon (EC) and total carbon (TC), as well as particle number count (PNC) across ultrafine particle sizes consistent with the size range of diesel engine emissions. DPM penetration through five commonly used P2 respirator filter models (W3206, 8577, 1720V, 8822 and 2400) was measured as a function of EC and TC in accordance with NIOSH 5040 as well as PNC using an Engine Exhaust Particle Sizer (EEPS), at three flow rates (95, 135 and 205L/min). Further analysis of one filter model was undertaken by an external laboratory using current standards certified methods and challenge aerosols, to enable comparison with the study results.

The aims of the research were:

- to determine whether current sodium chloride NaCl penetration test requirements adequately ascertain if Standards Australia certified respirator filters effectively filter out DPM
- to determine whether Standards Australia certified respirator filters effectively filter out DPM at flow rates representative of moderate to heavy work rates

- to determine whether DPM is effectively filtered out when PNC is measured.
- to determine whether 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 newly adopted AS ISO 16900.3 (Standards Australia Limited 2015) adequately assess whether P2 certified respirator filter media effectively filters out DPM.

Key Findings

- EC was effectively filtered out, as a filtering efficiency of less than 6% penetration was achieved for all of the filter models, when measured as EC penetration through the filter media at the standard specified flow rate of 95L/min.
- TC was effectively filtered out for two of the five filter models, when measured as TC penetration, at the standard specified flow rate of 95L/min.
- Filtering efficiency was below 6% penetration for four of the five filter models, at a flow rate of 95L/min when measured as PNC penetration.
- EC was effectively filtered out at 135 and 205L/min with the exception of one filter model at the higher flow rate.
- TC was filtered out effectively for all but one filter model at 135L/min and for two filter models at 205L/min.
- Particles were effectively filtered out for three of the five filter models, at flow rates of 135 and 205L/min.
- Results from external laboratory testing using standard challenge aerosols show that Paraffin Oil is a more conservative test than NaCl. Similarly, PNC penetration after 60 minutes of exposure time is more conservative than EC penetration.
- Initial findings indicate that it may be possible to streamline certification testing protocols by conducting tests at only two of the three proposed flow rates (95/135 and 205L/min), which would be a cost benefit to respirator manufacturers and ultimately respirator users, should the draft ISO standard be adopted for Australian workplaces.

The research findings suggest 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. Furthermore, certification testing is not conducted at flow rates representative of moderate to heavy work, despite indications of increased filter penetration with increasing flow rate. These findings have implications for workers required to wear respiratory protection, particularly those who are required to work at moderate to heavy 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 like DPM, 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 (Burton et al. 2016; Janssen 2003). 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. Although limited to one respirator filter model, the results of this study would indicate that Paraffin Oil may provide a more conservative estimate of exposure to DPM than NaCl and hence 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 DPM respiratory protection equipment, so as 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.

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1. Introduction

Diesel engines are used in a variety of contemporary workplaces, ranging from heavy industrial machinery to light passenger vehicles. Exposure to emissions from diesel engines occurs occupationally when working in the vicinity of diesel sources and environmentally via exposure to polluted air. Diesel engine emissions are known to cause irritant effects as well as being confirmed human carcinogens (World Health Organisation 2013). The emissions are also associated with an increase in cardiovascular mortality and morbidity (Brook et al. 2010).

Respirators are a widely used control measure to mitigate exposure to diesel particulate matter (DPM), the particulate fraction of diesel engine emissions. In Australia, AS/NZS 1715 (Standards Australia International Ltd & Standards New Zealand 2009) provides guidance on the appropriate selection of respiratory protection. DPM is generated by diesel engine combustion processes, and the standard AS/NZS1715 recommends for thermally generated particles like DPM, a minimum P2 half facepiece – replaceable filter or disposable facepiece respirator for worker exposures up to 10 times the occupational exposure standard. A Class P2 filter is defined as “used for protection against mechanically or thermally generated particulates or both”, whilst for a Class P3 filter “used in a half facepiece, a protection factor equivalent to a P2 filter is achieved” (Standards Australia International Ltd & 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 & 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).

Two published international studies evaluated filtering efficiency of half face respirators against diesel engine emissions. The first study (Janssen and Bidwell 2006) measured filtering efficiency as a function of elemental carbon (EC) using National Institute of Occupational Safety and Health (NIOSH) rated filters and found that P and R filters met filtering efficiency requirements, however N rated filters did not. N series filters are designated for workplaces free of oil aerosols, whilst R and P rated filters are rated for removal of oil-based liquid particulates (Code of Federal Regulations 1995). The second study (Penconek, Drążyk and Moskal 2013) found that DPM was more penetrating than the challenge aerosols designated for European Norm (EN) certified filters and the tested filters did not meet the specified filtering efficiencies.

Previous research (Burton et al. 2016) found that when P2 certified filters commonly used in Australian workplaces were challenged with diesel emissions from two diesel sources, filtering efficiency requirements were not met under all circumstances of diesel generated particles.

Increasing the flow rate through the respirator filter has been shown to decrease the filtering efficiency in multiple studies (Balazy et al. 2006; Eninger, Honda, Adhikari, et al. 2008; Eshbaugh et al. 2009). Peak inspiratory flow rates for various work rates range from 124L/min for moderate work with no speech to 275.4L/min for heavy work with speech (ISO 2007). The flow rates outlined in the ISO technical specification are consistent with work place studies (Caretti & Coyne 2006; Smith, Whitelaw & Davies 2013).

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).

In summary, Standards Australia approved respirator filters are not challenged with workplace contaminants at flow rates representative of moderate to heavy work rates. Published research which evaluates whether the current test for filtering efficiency specified in AS1716 (Standards Australia International Ltd & Standards New Zealand 2012) ensures workers are adequately protected against DPM is limited to one small scale study which found that not all tested filters met certification requirements (Burton et al. 2016). 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 (Janssen & Bidwell 2006; Penconek, Drążyk & Moskal 2013). Furthermore, there were no studies where penetration using DPM as the challenge aerosol was evaluated at flow rates representative of moderate to heavy workloads, nor were there studies which considered penetration as a function of particle number. However, studies measuring filtering efficiency using other challenge aerosols demonstrate decreased filtering efficiency as flow rate increases (Eninger, Honda, Adhikari, et al. 2008; Eshbaugh et al. 2009).

1.1 Key Research Objectives

Having regard to the findings in the literature review, four research aims were identified:

- To ascertain whether standards certified P2 respirator filter media used in Australian workplaces effectively filters out DPM, when challenged with emissions from a diesel engine and measured as penetration of EC and Total Carbon (TC) through the respirator filter media at the standards specified constant flow rate of 95L/min.
- To determine whether standards certified P2 respirator filter media used in Australian workplaces effectively filters out DPM, when challenged with emissions from a diesel engine and measured as penetration by Particle Number Count (PNC).
- To determine whether Standards Australia certified respirator filter media effectively filters out DPM at flow rates representative of moderate to heavy work rates, measured as penetration of EC, TC and PNC at constant flow rates of 135 and 205L/min.
- To evaluate whether 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 newly adopted AS ISO 16900.3 (Standards Australia Limited 2015) are adequate to assess whether P2 certified respirator filter media effectively filters out DPM.

1.2 Limitations and Constraints of the Study

- The study was confined to the efficiency of filter media with respect to challenge aerosol and flow rate and did not consider other factors which influence the level of protection provided to users, such as Total Inward Leakage (TIL). Additionally, the particulate matter component of diesel engine emissions was the focus of the study, given the adverse health impacts that have been associated with this phase. Gaseous components of the emissions, such as carbon monoxide, and nitrogen dioxide, were not evaluated.
- Filters were mounted inside an experimental chamber, with filtering efficiency evaluated at a constant air flow rate through the filter. These conditions were used to represent workplace use however whilst a constant air flow rate is used in Standard penetration test protocols, the respirator wearing worker would experience cyclical flow rates due to inhalation and exhalation.

- The number of replicates for each filter and flow rate was limited to 6-9 replicates per filter model and flow rate, leading to some 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 problem 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 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. Review of the Literature

2.1 Current Legislation and Standards for Occupational Exposure to DPM

Safe Work Australia has not designated an occupational exposure standard for diesel particulate matter (SafeWork Australia 2016). DPM is not specifically referenced in the Model Work Health and Safety regulations, however 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 2011).

The Australian Institute of Occupational Hygienists (AIOH 2013) states that "*In the absence of any more definitive data, the AIOH supports the use of an exposure standard of 0.1 mg/m*^{3} *DPM (measured as submicron elemental carbon) as being a balance between the factors of primarily minimising irritation, secondarily minimising any potential for risk of lung cancer to a level that is not detectable in a practical sense in the work force, and finally on the basis of setting a level achievable as best practice by industry and government*".

Various Australian mining industry regulatory bodies have adopted an 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).

Internationally, a number of countries have assigned exposure standards for DPM measured in various forms, as prescribed limits or guideline values, outlined in Table 2.1.

Table 2.1: International Occupational Exposure Standards for DPM

Country	Standard	8hour limit value (mg/m^3)
United States (MSHA 2001)	MSHA - Permissible exposure level	0.16 TC (equivalent to 0.12 EC)
Austria (IFA 2016)	TRK value, respirable aerosol - Underground mining	0.3 (STEL 1.2)
	TRK value, respirable aerosol – other exposures	0.1 (STEL 0.4)
Ireland (IFA 2016)	Diesel Exhaust dust, respirable	0.15 (Particulates <0.1µm)
Poland (IFA 2016)	Diesel Exhaust dust, respirable	0.5
Germany (DieselNet 2016)	Whole diesel particulate – Tunnelling and non-coal mining	0.3 EC
	Whole diesel particulate – Other applications	0.1 EC

IFA - Institute for Occupational Safety and Health of the German Social Accident Insurance

TC – Total carbon TRK – Technical Guidance Concentration STEL – Short Term Exposure Limit

2.2 Published Exposure Data

2.2.1 Australian Workplaces

Exposure data for various coal mines in NSW reported DPM exposures measured as EC ranging from 0.01-0.55 mg/m^3 (Mace 2008; Rogers & Davies 2005). Underground metalliferous mine exposures range from 0.01-0.42mg/m^3 EC (AIOH 2013).

The Australian Government Department of Defence, in a fact sheet regarding diesel exhaust emissions for a specific army vehicle states that "*levels of exposure to DPM were well within the AIOH recommended occupational exposure standard of 0.1mg/m^3, measured as submicron elemental carbon*" (Defence Work Health and Safety 2012). Data on other diesel exposures within Defence were not publicly available.

2.3 Control of Exposure to DPM

Control of exposure to DPM should be via the Hierarchy of Control, with priority given to controlling exposures at the source, rather than at the receiver (SafeWork Australia 2011). Increasing regulatory requirements aimed at reducing emissions from diesel engines, including more stringent emissions and testing criteria, have led to better technologies with regard to the engines themselves, cleaner burning fuels and more effective exhaust treatment systems. In Australia these requirements are specific to on road vehicles, and there is a range of new and old technology diesel engines in workplaces.

Respiratory protection, whilst at the lowest level of the control hierarchy, remains an important workplace control to supplement other management strategies or where higher order controls are not effective (Cherrie 2009; Standards Australia International Ltd & Standards New Zealand 2009).

The nine NSW coal mines for which exposure data were reported (Mace 2008) utilised a number of control strategies including low sulphur fuel, ventilation techniques, engine maintenance programs, exhaust filters, a tag board system to monitor the number of engines in the common space, road design improvements and an education system to raise awareness of how to minimise exposure to DPM during operation of equipment. Personal protective equipment was also identified as a control for these mine sites with a P2 respirator filter impregnated with charcoal recommended.

2.4 Respiratory Protection to Mitigate Exposure to DPM

2.4.1 Selection

Diesel particulate matter consists of thermally generated particles, hence a P2 or P3 filter is required, providing a minimum protection factor of 10 times the occupational exposure standard (Standards Australia International Ltd & Standards New Zealand 2009). Depending on the face-piece that is used in conjunction with the filter, the protection factor can increase to 100 times the occupational exposure standard. These protection factors assume that the respirator has been well fitted and the wearer is clean shaven and trained in its use (Standards Australia International Ltd & Standards New Zealand 2009). A search of key Australian manufacturer /

supplier websites revealed that from an end user perspective there is little specific guidance available for the selection of a respirator against DPM, as summarised in Table 2.2.

Table 2.2: Australian Respirator Supplier's recommendations for respiratory protection

Supplier	Recommendation for DPM
3M Australia	A search for diesel recommends the 9923V P2 disposable respirator with nuisance level organic vapour relief.
Draeger Safety Pacific	A technical brochure recommends the Dräger X-plore 1320V and 1720V, with and without odour, and provides filtration efficiency data for these filters
Honeywell Analytics	No specific recommendation for DPM
Moldex	Diesel is not listed in the Chemical Selection Guide however the technical brochure recommends the 2400P2 disposable respirator with nuisance odour relief
MSA Australia	No specific recommendation for DPM
Paftec	No specific recommendation for DPM
S.E.A. Group	No specific recommendations for DPM
Scott Safety	No specific recommendations for DPM

(3M 2013; Draeger Safety Pacific Pty Ltd 2011; Honeywell International Inc. 2016; Moldex-Metric Inc. 2016; MSA Australia 2016; Paftec 2016; Scott Safety Australia 2014; The S.E.A. Group 2015)

Anecdotal evidence from suppliers and end users in the mining sector indicates that users are selecting a range of P2 and P3 respirators, often with a carbon layer to provide some additional protection against volatile organics contained in diesel exhaust emissions.

2.4.2 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 (CEN 2001; Code of Federal Regulations 1995; Standards Australia International Ltd & Standards New Zealand 2012).

In Australia, respiratory protection is evaluated in accordance with AS/NZS 1716 (Standards Australia International Ltd & Standards New Zealand 2012). A number of criteria are evaluated to gain Australian Standards approval, including 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 & 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 & 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 filter is achieved if the penetration through the filter media is less than 6% and for P3 less than 0.05% (i.e. filtering efficiency is greater than 94% and 99.95% respectively).

Internationally, test protocols in standards to evaluate filtering efficiency differ in relation to challenge aerosols and flow rates as summarised in Table 2.3 (CEN 2001; Code of Federal Regulations 1995). 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 2012, 2013). Consistent with European Standards, NaCl or Paraffin Oil are recommended as the challenge aerosols for certification testing (Standards Australia Limited 2015).

Table 2.3: Required Filter Efficiency, Flow rates and Challenge Aerosols

Reference Standard	Filter	Filtering Efficiency (%)	Flow Rate (L/min)	Challenge Aerosol
AS / NZS 1716: 2012	P2	94	30 / 95	NaCl
	P3	99.95		
NIOSH 42CFR84: 1995	N, P or R95	95	85	NaCl (N)
				DOP (P and R)
	FFN, P or R100	99.7	85	NaCl (N)
				DOP (P and R)
EN 149: 2001 and EN143: 2000 (CEN 2000)	P2 / FFP2	94	95	NaCl / Paraffin Oil
	P3 / FFP3	99	95	
ISO 16900-3: 2012 ISO/TS 16975-1:2016	F1-F5	80-99.99	85 / 135 / 205 / 255	NaCl / Paraffin Oil

(CEN 2000, 2001; Code of Federal Regulations 1995; ISO 2012, 2016; Standards Australia International Ltd & Standards New Zealand 2012)

2.4.3 Limitations of current 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 a number of 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.

AS/NZS1716 outlines the minimum requirements for approval of respiratory protection in Australia and New Zealand. Recognition of potential limitations of the current testing protocol by the Joint Technical Committee SF-010 is indicated by the preface of AS/NZS 1716, stating that "*It is anticipated that a new series of ISO standards will be published in the next few years that will incorporate major developments that will address most, if not all, concerns highlighted in the previous edition. When such ISO standards are published, it is planned that they will be adopted as the next revision of AS/NZS 1716*" (Standards Australia International Ltd & Standards New Zealand 2012). The specific concerns are not highlighted in the document, however limitations of the current standard with respect to challenge aerosol and flow rate are discussed below.

2.4.3.1 Challenge Aerosol

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

These differences were considered by Penconek, Drążyk & Moskal (2013) who evaluated European Standard-certified half masks against DPM and reported that the DPM was more penetrating than the standard challenge particles of NaCl, paraffin oil and DOP. Filtering efficiency of DPM mass did not meet the standards set for certification, with 11-16 % of particles measured as penetrating the filtering face-piece (FF) FFP2 filters and 14-25 % penetration of particles for the FFP3. The method used the gravimetric load on the respirator filter to evaluate penetration, which would not be specific to DPM. Additionally, they did not report whether they evaluated the efficacy of the seal to the respirator head-form. It is unclear why the FFP3 filters had a higher penetration that the FFP2 rated filters. Another limitation of the study is that the testing was conducted at a flow rate through the filter of 30L/min which is lower than the flow rate of 95L/min designated in the standard (CEN 2000).

In another study by the same authors (Penconek et al. 2013) fibrous filters used for aerosol filtration were challenged with DPM, using varying fuel sources, to generate particles of different morphology. The authors reported that "*small (<0.1 µm) more spherical in shape aggregates are filtered with higher efficiency than small dendrite-like aggregates*".

Contrary to this finding, Janssen and Bidwell (2006) evaluated the performance of US NIOSH certified electret filters by exposing them to DPM and measuring particle size distribution and penetration of EC. EC penetration was not detected for the P95 filter. The R95 filters met certification requirements for filtering efficiency. For both P and R filters, EC penetration was lower than the standard test challenge aerosols. N95 filters did not demonstrate acceptable filtration efficiency, however are not rated for use against DPM given it is an oily residue. P and R respirators are rated as efficient against atmospheres containing oily residues, however an R respirator should only be used for one shift in this type of atmosphere (Code of Federal Regulations 1995). A confounding factor in this study was that the DPM load on the filter was determined to be higher than typical workplace exposures. The testing was however conducted at a flow rate of 25L/min which is lower than the 95L/min designated in the NIOSH standard (Code of Federal Regulations 1995).

Cho (2011) compared pressure drop and filtering efficiency of NaCl and welding fumes and found that efficiency was higher for NaCl, however the pressure drop increased due to accumulation of welding fumes on the filter.

2.4.3.2 Flow Rate

As summarised in Table 2.3 filtering efficiency is measured at designated flow rates internationally, including 30, 85 and 95 L/min. International Standards Organisation (ISO) provide reference tables of peak flow rate for various body sizes and work rates, both with and without speech (ISO 2007), as adapted and summarised in Table 2.4.

Table 2.4: Estimation of peak inspiratory flow rates for conditions of speech and no speech, for a person with a body surface area of 2.11m^2 (adapted from ISO 2007).

Work Rate	Average Metabolic Rate (W/m^2)	Peak Flow Rate (no speech) L/min	Peak Flow Rate (speech) L/min
Resting	65	57	141.6
Light work	100	82.2	177.6
Moderate work	165	124.2	231
Heavy work	230	163.8	275.4
Very heavy work	290	198.6	310.8
Very, very heavy work (2 h)	400	259.8	367.8
Extremely heavy work (15 min)	475	300	402.6
Maximal work (5 min)	600	364.2	455.4

These data demonstrate that the flow rates used in the current testing protocols underrepresent workers required to work at moderate or greater work rates, especially if communication is required. Even at rest, the peak flow rate exceeds the 95L/min designated in the AS/NZS test protocol if communication is required.

The technical specification data are supported by workplace studies, such as (Smith, Whitelaw and Davies 2013) who report that for a cohort of respirator wearing miners the peak inspiratory airflow ranged from 80.5 L/min at rest to 323 L/min for the highest work rate measured, during speech. Jannsen (2003) and Caretti and Coyne (2006) also suggest that a higher airflow breathing rate occurs in the workplace than the flow rates at which filtering efficiency is evaluated.

The draft ISO performance standard (ISO 2016) aims to provide a consistent approach and recommend a range of Protection Classes for a range of Work Rates. The work rates at which testing will be required are aligned with the flow rates reported in 2.6.3.2.

In a study where penetration of nanoparticles was measured (Balazy et al. 2006), two types of N95 respirators were challenged with NaCl particles at 30 L/min and 85 L/min. Whilst the filtering efficiency met certification requirements at the lower flow rate, filtering efficiency did not meet the 95% threshold required for certification at the higher flow rate as shown in Figure 2.1. Additionally, penetration was found to increase with increasing flow rate.

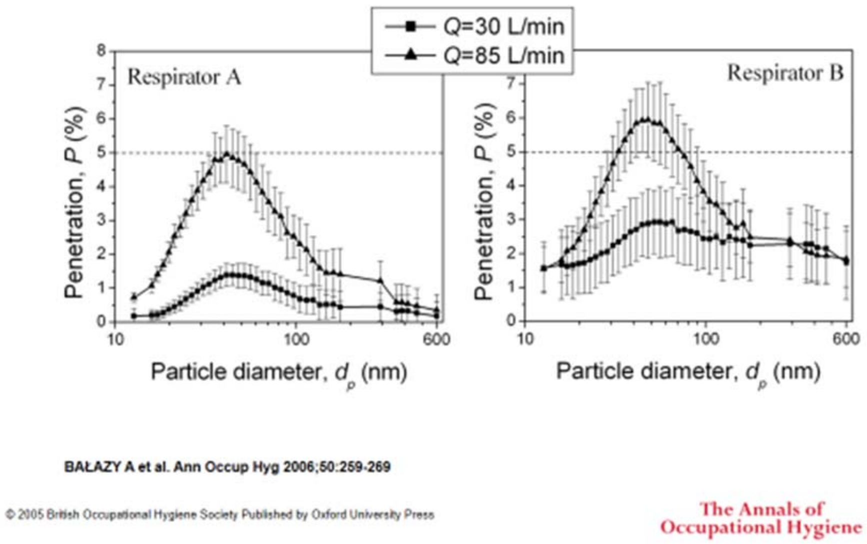

Figure 2-1: Effect of the inhalation flow rate on the penetration of particles through Respirator A and Respirator B (n = 10) (Balazy et al. 2006).

Eshbaugh and co-workers (2009) evaluated N95 and P100 respirators at flow rates of 85, 270 and 360 L/min. Their findings demonstrated that penetration of NaCl increased as flow rate increased. Similar trends were reported when performance of N95 and N99 respirators against NaCl and viruses at varying flow rates were evaluated (Eninger, Honda, Reponen, et al. 2008) and when N95 respirators were evaluated against nanoparticles at flow rates ranging from 85 - 360 L/min, using NaCl as the challenge aerosol (Haghighat et al. 2012). In a study where P 100 filters were challenged with combustion aerosols from various sources, penetration as a function of particle size increased when the flow rate increased from 30L/min to 85L/min, however decreased when the flow rates were increased from 85 to 135 L/min (He et al. 2013).

2.4.4 Impact of flow rate and challenge aerosol on filter performance

Revoir and Bien (1997) outline that properties influencing the capture of particles by filter media are related to:

- the characteristics of the particle including size, shape, density and electrical charge;
- the properties of the filter media including diameter, density and electrical charge
- the mechanisms of how the filter media capture particles (as described below and shown in Figure 2.2):
    - inertial impaction – large particles with too much inertia are captured when the airstream flow is diverted by the filter
    - interception – larger particles may be intercepted by the filter fibres
    - diffusion – smaller particles are bombarded by the airstream and diverted into contact with the fibre filter
    - electrostatic attraction – oppositely charged particles to fibre filter are captured, most effective for smaller particles.

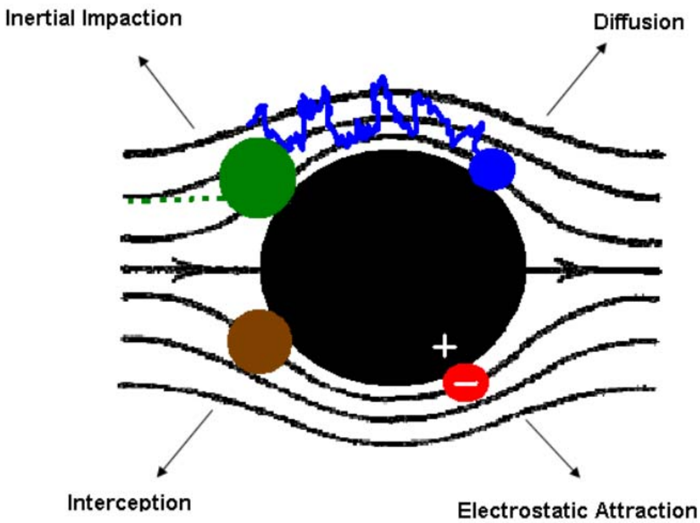

Figure 2-2: Filtration mechanisms for capture of particles (Hinds 1999)

Each of these different filter capture mechanisms will play a more dominant role at various particle sizes. The most penetrating particle size (MPPS) describes the particle size range that is most difficult to remove from the air stream, illustrated by the example provided in Figure 2.3. If penetration is evaluated at the most penetrating particle size, then this provides a worst case evaluation of filtering efficiency.

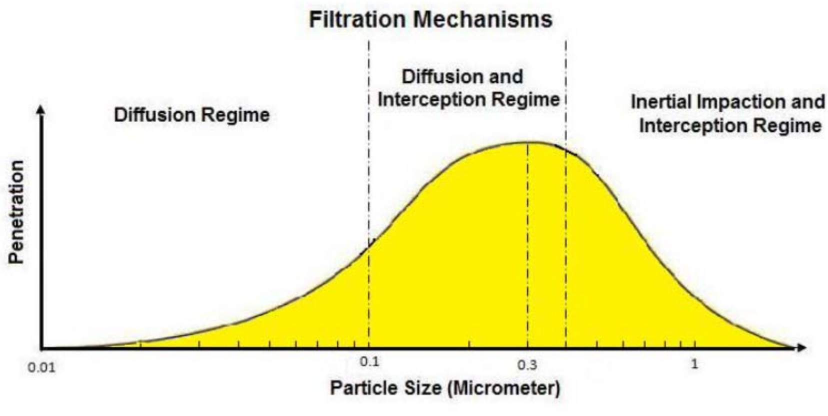

Figure 2-3: Example of most penetrating particle size and filtration mechanisms that apply with respect to particle size and filter efficiency (Haghighat et al. 2012)

The study by Balazy et al. (2006) demonstrates that penetration of particles through the filter media is linked to particle size and flow rate, with a parabolic like curve around the Most

Penetrating Particle Size, as shown in Figure 2.3. The MPPS calculated varied with respirator type.

He et al. (2013) evaluated the performance of a half face respirator with NIOSH P100 rated filters at a range of flow rates. The filter was challenged with combustion products from burning wood, paper and plastic and penetration was determined as a function of particle number. The results demonstrated that the variables of flow rate, particle size and aerosol source affected filter performance with penetration most significant in the ultrafine range between 0.04-0.2 µm diameter.

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 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, BerryAnn and Szalajda 2013).

2.5 Evaluation of Research Methods

2.5.1 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, a mass based method, 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 & Cary 1996; Bunn et al. 2002; Liukonen, Grogan & Myers 2002). EC has also been linked to potential adverse health outcomes and has an exposure standard in Australian mining regulations based on minimizing these adverse health outcomes.

Noll (2006) agrees that EC is a good marker for DPM but queries whether it is still as effective with newer diesel technology, given lower levels of particulate mass and hence EC emissions.

The measurement of EC relies on a Thermo-optical method of analysis (NIOSH 2003). This analysis reports both EC and OC, whilst TC can be calculated by summing EC and OC.

Direct measurement techniques are also available to measure EC, including instruments such as the aethelometer and Flirtec DPM monitor. These techniques rely on Laser light scattering and use an internal instrument calibration factor to convert the TPM (Total Particulate Matter) to EC. This internal calibration factor is problematic as it will vary with the characteristics of the engine (Davies 2013). Whilst more convenient and inexpensive to use a direct reading instrument to measure EC, until a direct reading device can be validated, NIOSH 5040 is the preferred method.

In the US, the exposure limit measurement criteria is TC, however, in recognition that TC concentration may be increased by other carbon sources, such as cigarette smoke, the EC concentration is measured and a conversion factor is used to calculate TC. This conversion factor will vary depending on the diesel engine source (MSHA 2001). A recent study explored the relationship between EC and TC and found a strong correlation for metal / non metal underground mines in the US, but did not go so far as to recommend an accurate ratio. For underground coal mines in Australia, the study reported a conversion factor of 1.27 (equivalent to an EC/TC ratio of 0.78) with a range of about 19% (Noll et al. 2014). However, available data at lower exposure levels were excluded when determining the TC/EC ratio which may have incorrectly weighted the reported findings.

2.5.2 Measurement of Particle Number Count

There are a number of 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. An alternative instrument is the Engine Exhaust Particle Sizer (EEPS) which 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 Appendix I (Standards Australia International Ltd & Standards New Zealand 2012), was developed in order to evaluate the key research objectives. Reference was also made to International Standards ISO16900-3 Part 3: Determination of Particle Filter Penetration (ISO 2012). Unlike these referenced standards, DPM was used in place of sodium chloride as the challenge aerosol. The sampling methodology required the use of an experimental chamber which was purpose built.

3.1 Respirator Filter Media

Five P2 respirator filter models known to be used in Australian coal mines (Kristy Prior 2015) to protect workers from exposure to DPM were tested, including respirator filters which utilise electret and mechanical type filter media. Three 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.

3.1.1 1720V Particulate Respirator

The Dräger X-plore 1720V Odour respirator is manufactured by Dräger and supplied by Draeger Safety Pacific in Australia. It is a P2 rated respirator in accordance with AS1716 (Standards Australia International Ltd & Standards New Zealand 2012), as well as a FFP2 rated filter in accordance with European Norm EN149:2001/AC (CEN 2001). CoolSAFE™ filter material is used with the addition of an activated carbon layer to protect from nuisance odours.

3.1.2 SuperOne™ W3206 Particulate Respirator

The SuperOne™ W3206 respirator is manufactured and supplied by Honeywell Safety Products Australia and supplied with Freudenberg Disposable diesel exhaust filters. It is rated as a P2 filter (Standards Australia International Ltd & Standards New Zealand 2012) and features an exhalation valve.

3.1.3 8577 Particulate Respirator

The 8577 respirator, manufactured by 3M™ and supplied by 3M™ Australia, is rated as a P2 particulate respirator (Standards Australia International Ltd & Standards New Zealand 2012). It features an exhalation valve and offers protection against nuisance level organic vapours. This respirator is also rated as a P95 filter (Code of Federal Regulations 1995).

3.1.4 8822 Particulate Respirator

The 8822 respirator, manufactured by 3M™ and supplied by 3M™ Australia, is rated as a P2 particulate respirator and is a cupped respirator, featuring an exhalation valve (Standards Australia International Ltd & Standards New Zealand 2012). It is also rated as an FFP2 respirator in accordance with European Norm EN149:2001/AC (CEN 2001).

3.1.5 Moldex 2400 Particulate Respirator

The 2400 respirator, manufactured and supplied by Moldex-Metric Inc, is rated as a P2 particulate respirator (Standards Australia International Ltd & Standards New Zealand 2012). It contains an exhalation valve and added carbon layer to remove nuisance level organic vapours. The Moldex Chemical SelectionGuide states that Moldex products should not be used to protect against Diesel Exhaust (Moldex-Metric Inc. 2016) however the brochure states that it is suitable for mining operations where diesel particulate matter (DPM) is present. The packaging also states that it is an N95 filter (Code of Federal Regulations 1995).

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

Initially it was intended to utilise the experimental chamber developed in a previous study (Burton et al. 2016). Following the literature review and because this study also aimed to measure particle number count, the experimental chamber was rebuilt to improve mixing of emissions within the chamber and to be constructed of steel to decrease potential particle losses due to diffusion. The chamber was approximately 1.46m high and 0.56m in diameter, with a volume of approximately 0.36m^3.

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 2003). 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 Sunset Laboratories, USA, and Coal Mines Technical Services using the principles of NIOSH Method 5040 (NIOSH 2003).

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.

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 and attached to a stainless steel backing plate. The exhalation valves were sealed using Bostik Blu Tac. The filters were sealed onto the adapter around the facial seal by a hot melt gun.

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. Flow through the filter was adjusted to 95L/min, 135 or 205L/min ± 5L/min. These flow rates were chosen to represent the upper flow rate in the current Standards Australia penetration test as well as the flow rate outlined in the ISO technical standard representing heavy work (ISO 2007; Standards Australia International Ltd & Standards New Zealand 2012).

Six to nine replicate tests were conducted, for each of the filters at 95, 135 and 205 L/min. Sampling occurred over a one hour period which was considered to be representative of the time that a worker may reasonably use a negative pressure respirator in a workplace environment without removal and is recommended by the UK HSE as the maximum continuous wear time (HSE 2013). PNC was recorded every 15 minutes over the one hour sampling period.

The sampling configuration is shown in Figures 3.2, 3.3 and 3.4.

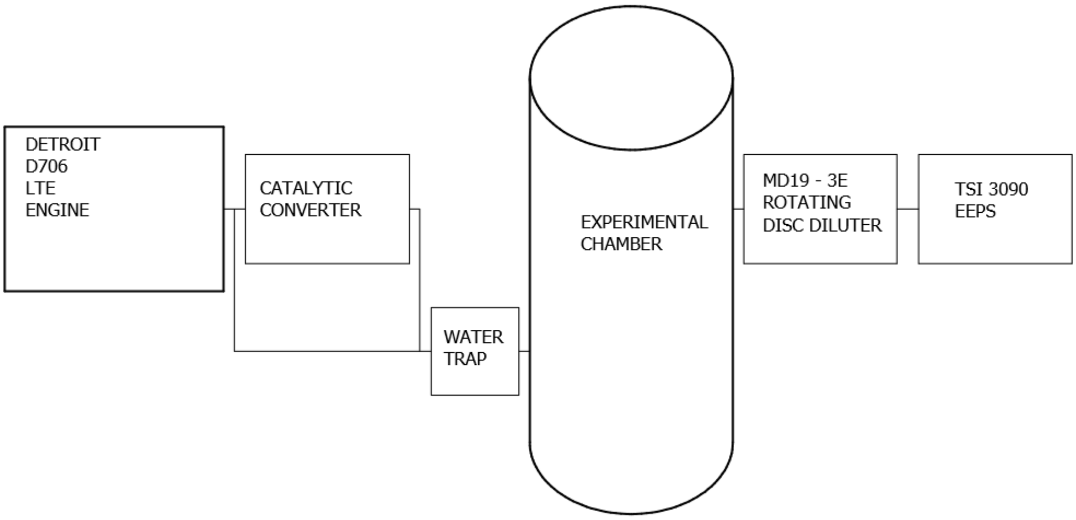

Figure 3-1~~2~~: Initial Project Design

Figure 3-2~~3~~: Sampling Configuration

Figure 3-34: Filter Samples Mounted Inside the Experimental Chamber Showing Post Filter Port A, Post Filter Port B and the Pre Filter Sampling Port.

3.6 Method Validation

3.6.1 Testing without filter in place

The setup was tested 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 to confirm 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.

3.6.3 Leak Testing of Used Filters

Used respirators were retained and randomly evaluated post sampling to ensure that there was no leakage via the seals to the adapter and exhalation valve.

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, one filter model was sent to INSPEC, 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 & Standards New Zealand 2012) and Paraffin Oil which is specified as an alternative to NaCl in AS16900.3 and EN143/EN149 (CEN 2000, 2001; Standards Australia Limited 2015).

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 2003):

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

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.

Penetration of EC and TC was calculated using the equation described in Section 2.6.2.

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 using the equation in Section 2.6.2.

3.8.1 Treatment of Results at or Below the Limit of Detection

A number of 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 2003). 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, Ignacio & American Industrial Hygiene Association Exposure Assessment Strategies Committee 2006).

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 of mean (M), standard deviation (SD) and number of samples (n) were used to summarise the sampling data.

Data were 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 sampling was conducted between the 5th November 2015 and the 22nd of August 2016. Ninety paired pre and post filter samples were collected, for the five filter models (W3206, 8577,1720V, 8822, 2400), at three flow rates (95L/min, 135L/min and 205L/min).

4.1 Temperature and Humidity

The temperature averaged 28.7°C within the experimental chamber (SD = 4.4 n=92). Relative Humidity averaged 47.2% within the experimental chamber (SD = 16.0 n=92).

4.2 Pre filter EC Concentration

The EC concentration in the experimental chamber averaged 1.1mg/m^3 (*SD* = 0.2, *n* = 92). This mean was slightly above the desired Pre Filter EC concentration of 1.0mg/m^3, however was within the Guidance for General Excursions above the Occupational Exposure Standard and is valid (SafeWork Australia 2012).

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 0.7 (*SD*=0.1, *n*=92).

4.5 Penetration Test Results

4.5.1 EC and TC Penetration

Tables 4.1 - 4.3 report the EC and TC penetration results at each of the tested flow rates, for all filters combined and for each of the filter models.

Table 4.1: EC and TC Penetration at 95L/min

Filter	EC Penetration (%) 95L/min				TC Penetration (%) 95L/min			
	M	*SD*	*95% UCL*	*n*	*M*	*SD*	*95% UCL*	*n*
All Filters	0.8	0.8	1.1	33	4.1	4.5	5.7	33
W3206	0.9	0.3	1.3	6	3.5	1.0	4.5	6
8577	0.7	0.5	1.1	9	1.0	0.9	1.7	9
1720V	1.2	1.0	2.3	6	6.2	7.1	13.7	6
8822	0.4	0.1	0.5	6	5.8	4.5	10.5	6
2400	0.9	1.5	2.5	6	5.4	5.3	11.0	6

Collectively for all filters, requirements for penetration to be less than 6% at 95L/min for EC and TC were met. When considered by individual filter model, the mean EC penetration and 95% UCL for each individual filter model was below 6%. Mean TC penetration was also below 6% for all filter models with the exception of the 1720V filter, which extends above 6%. The 95% upper confidence level for TC penetration exceeds 6% for the 1720V, 8822 and 2400 filter.

Table 4.2: EC and TC Penetration at 135L/min

Filter	EC Penetration (%) 135L/min				TC Penetration (%) 135L/min			
	M	*SD*	*95% UCL*	*n*	*M*	*SD*	*95% UCL*	*n*
All Filters	1.6	1.5	2.1	29	3.7	4.2	5.4	29
W3206	2.3	1.4	3.8	6	5.3	1.5	6.8	6
8577	0.6	0.4	1.1	6	0.2	0.1	0.3	6
1720V	2.1	2.1	4.3	6	5.3	6.0	11.6	6
8822	1.5	1.2	3.0	5	3.3	4.4	8.7	5
2400	1.4	1.4	2.8	6	4.6	5.0	9.9	6

At a continuous air flow rate through the respirator filter of 135L/min the mean EC penetration was below 6% for all filters combined and individually, as was the 95% UCL. Mean TC penetration was below 6% for all filter models combined and each individual filter model, however the 95% UCL exceeded 6% TC penetration for all filter models except the 8577.

Table 4.3: EC and TC Penetration at 205L/min

Filter	**EC Penetration (%) 205L/min**				**TC Penetration (%) 205L/min**			
	M	***SD***	***95% UCL***	***n***	***M***	***SD***	***95% UCL***	***n***
All Filters	2.5	3.9	4.0	28	5.5	5.7	7.7	28
W3206	2.5	1.3	3.9	6	6.4	2.3	8.8	6
8577	0.4	0.2	0.6	6	0.9	0.8	1.8	6
1720V	7.8	5.8	13.9	6	12.0	8.8	21.2	6
8822	0.5	0.3	0.9	5	5.8	1.5	7.6	5
2400	0.4	0.2	0.7	5	1.7	1.7	3.9	5

At 205L/min the mean EC penetration and 95% UCL was below 6% for all filters, with the exception of the 95%UCL for the 1720V filter. The mean TC penetration was below 6% for all filters combined as well as the 8577, 8822 and 2400 filter model. 95%UCL was considered, 6% TC penetration was met by the 8577 and 2400 filter models however was exceeded for all filter models combined as well as the W3206, 1720V and 2400 filters.

4.5.2 Particle Number Count Penetration

Table 4.4 reports the particle number count penetration results at each of the tested flow rates, for all of the filters combined and for each of the filter models individually, for particle midpoint diameters ranging between 25.5 and 560nm, after 60 minutes of exposure to the diesel emissions. This exposure time is consistent with the exposure time for the EC and TC penetration results. Table 4.5 reports the initial penetration results by Particle Number Count.

Table 4.4: Particle Number Count Penetration at 95, 135 and 205L/min After 60 Minutes Exposure for Particles 25.5 – 560nm

Filter	Penetration (%) 95L/min				Penetration (%) 135L/min				Penetration (%) 205L/min			
	M	*SD*	*95% UCL*	*n*	*M*	*SD*	*95% UCL*	*n*	*M*	*SD*	*95% UCL*	*N*
All Filters	3.2	2.4	4.1	33	4.8	3.9	6.2	29	5.9	3.3	7.2	28
W3206	2.5	2.0	4.6	6	4.4	1.5	6.0	6	9.7	4.3	14.2	6
8577	5.8	2.6	7.7	9	7.1	6.8	14.3	6	7.2	2.2	9.5	6
1720V	1.9	1.8	3.8	6	4.2	2.4	6.7	6	4.6	1.4	6.0	6
8822	2.7	1.1	3.9	6	1.5	0.3	1.8	5	4.6	0.4	5.1	5
2400	2.1	0.8	2.9	6	6.1	3.4	9.7	6	2.8	0.7	3.7	5

At a flow rate of 95L/min the mean penetration measured by PNC was below 6% for all filter models combined, as well as each individual filter model, with the 95%UCL also below 6% for all filters combined and the W3206, 1720V, 8822 and 2400 filter models, however exceeded 95%UCL for the 8577 filter model.

For the flow rate 135L/min mean penetration by PNC was below 6% for all filter models, with the exception of the 8577 filter. The 95%UCL was below 6% penetration for the 8822 filter model and exceeded this limit for all other filters.

At 205L/min, mean and 95%UCL PNC penetration results were at or below 6% for the 1720V, 8822 and 2400 filter models, however exceeded this limit for all filters combined as well as the W3206 and 8577 filters.

Table 4.5: Initial Particle Number Count Penetration at 95, 135 and 205L/min for Particles 25.5 – 560nm

Filter	Penetration (%) 95L/min				Penetration (%) 135L/min				Penetration (%) 205L/min			
	M	*SD*	*95% UCL*	*n*	*M*	*SD*	*95% UCL*	*n*	*M*	*SD*	*95% UCL*	*N*
All Filters	2.7	1.9	3.4	32	3.8	3.7	5.1	32	5.3	3.2	6.5	29
W3206	2.5	2.1	4.8	6	3.8	1.7	5.6	6	9.1	2.5	11.7	6
8577	4.5	2.1	6.1	9	6.7	6.0	11.8	8	7.2	3.1	10.1	7
1720V	1.4	0.8	2.2	6	2.0	1.3	3.2	7	2.8	0.9	3.7	6
8822	1.8	0.9	2.8	6	0.9	0.2	1.1	5	3.0	0.5	3.7	5
2400	2.2	1.4	3.9	5	4.4	1.9	6.3	6	3.2	0.5	3.9	5

The penetration results calculated after initial exposure to the diesel emissions were lower than the results obtained after 60 minutes of exposure, indicating that penetration of particles by PNC had increased over the one hour exposure time.

At a flow rate of 95L/min the mean penetration measured by PNC was below 6% for all filters, whilst the 95%UCL was also below 6% for all filters with the exception of the 8577 filter model.

At 135 L/min, the mean penetration levels and 95% UCL were below 6% for all filters combined as well as the W3206, 1720V, 8822 and 2400 filter models. The 8577 filter exceeded 6% penetration by both mean and 95% UCL.

At 205L/min, the 1720V, 8822 and 2400 filter model mean and 95% UCL penetrations were below 6% penetration, however the 95%UCL exceeded 6% PNC penetration for all filter models combined and the mean and 95%UCL were exceeded for the W3206 and 8577 filter models.

4.5.3 Effect of Filter Model on Penetration through the Respirator Filter

Consistent with the variation in penetration shown in Tables 4.4 and 4.5 and Figure 4.1, respirator filter model was shown to have a significant effect on filter penetration by a one-way ANOVA Welch test for EC, TC and PNC penetration as equal variances were not assumed:

EC	F (4,38) = 6.11, $p = 0.001$
TC	F (4,36) = 26.41, $p < 0.001$
Initial PNC	F (4,42) = 9.67, $p < 0.001$
60min PNC	F (4,43) = 5.71, $p = 0.001$

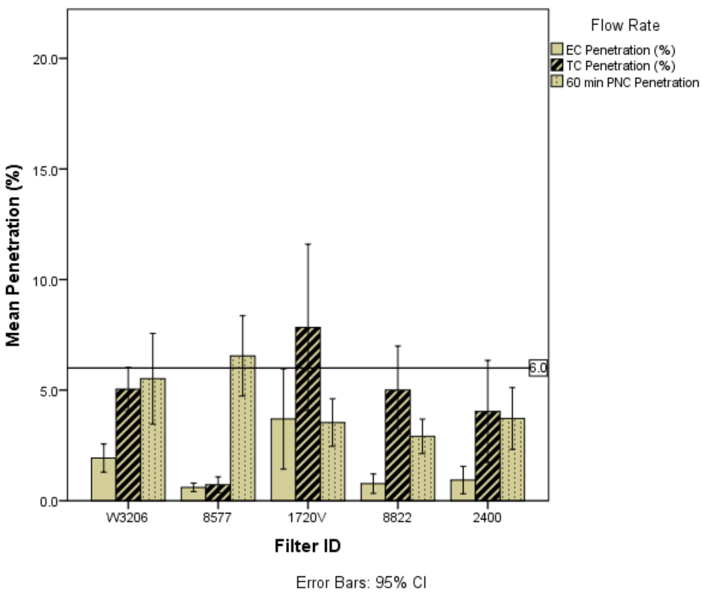

Figure 4-1: Effect of Filter Model on EC, TC and 60 minute PNC Penetration, Mean ± 95% Confidence Interval, n = 6-9, Reference Line represents allowable level of 6% Penetration

4.5.4 Effect of Flow Rate on Penetration through the Respirator Filter

The effect of flow rate through the filter on mean EC, TC, PNC initial and PNC 60minute penetration was compared using a One-Way ANOVA, with results reported in Table 4.6 for each filter model combined as well as considered separately. The effect of flow rate on TC penetration was not found to be significant however was found to be significant for EC and PNC penetration using the Welch test.

No significant differences were identified in Post-Hoc analyses of the EC and TC penetration results for all filter models or for each individual filter model.

There was a significant difference (p<0.05) between 95 and 205L/min for both the initial and 60 minute PNC penetration results for all filter models combined. There was also a significant mean difference in initial and 60minute PNC penetration for the W3206 and 8822 filter models, between 95 and 205L/min as well as between 135 and 205L/min, for the 8822 filter model for the initial PNC penetration, the mean difference between 95L/min and 205L/min, had a p value = 0.051.

Table 4.6: Effect of Flow Rate on Penetration through Respirator filters

	EC Penetration (%)	TC Penetration (%)	Initial PNC Penetration (%)	60 minute PNC Penetration (%)
All Filters	$^*F(2,45) = 4.80$, $p = 0.013$	$F(2,90) = 0.94$, $p = 0.394$	$^*F(2,54) = 7.01$, $p = 0.002$	$^*F(2,56) = 7.74$, $p = 0.001$
W3206	$F(2,17) = 3.40$, $p = 0.061$	$F(2,17) = 4.56$, $p = 0.028$	$F(2,17) = 15.61$, $p < 0.001$	$F(2,7) = 9.99$, $p = 0.002$
8577	$F(2,20) = 0.79$, $p = 0.471$	$^*F(2,8) = 5.35$, $p = 0.032$	$^*F(2,12) = 2.11$, $p = 0.166$	$^*F(2,13) = 1.22$, $p = 0.326$
1720V	$^*F(2,8) = 3.70$, $p = 0.075$	$F(2,18) = 1.46$, $p = 0.262$	$F(2,18) = 2.53$, $p = 0.111$	$F(2,18) = 3.31$, $p = 0.063$
8822	$^*F(2,6) = 2.37$, $p = 0.173$	$F(2,15) = 0.75$, $p = 0.492$	$^*F(2,7) = 38.74$, $p < 0.001$	$^*F(2,8) = 77.64$, $p < 0.001$
2400	$^*F(2,16) = 0.58$, $p = 0.438$	$F(2,16) = 1.02$, $p = 0.386$	$F(2,15) = 3.10$, $p = 0.079$	$^*F(2,9) = 4.54$, $p = 0.045$

* Equal variances were not assumed for these results, hence the Welch test was used to test the equality of means.

Post hoc analyses where equal variances were assumed were performed using Tukey's HSD, where equal variances were not assumed Post Hoc analysis were conducted using Games-Howell.

Mean penetration by respirator filter model is shown in Figure 4.2-4.4 for each of the flow rates 95, 135 and 205L/min.

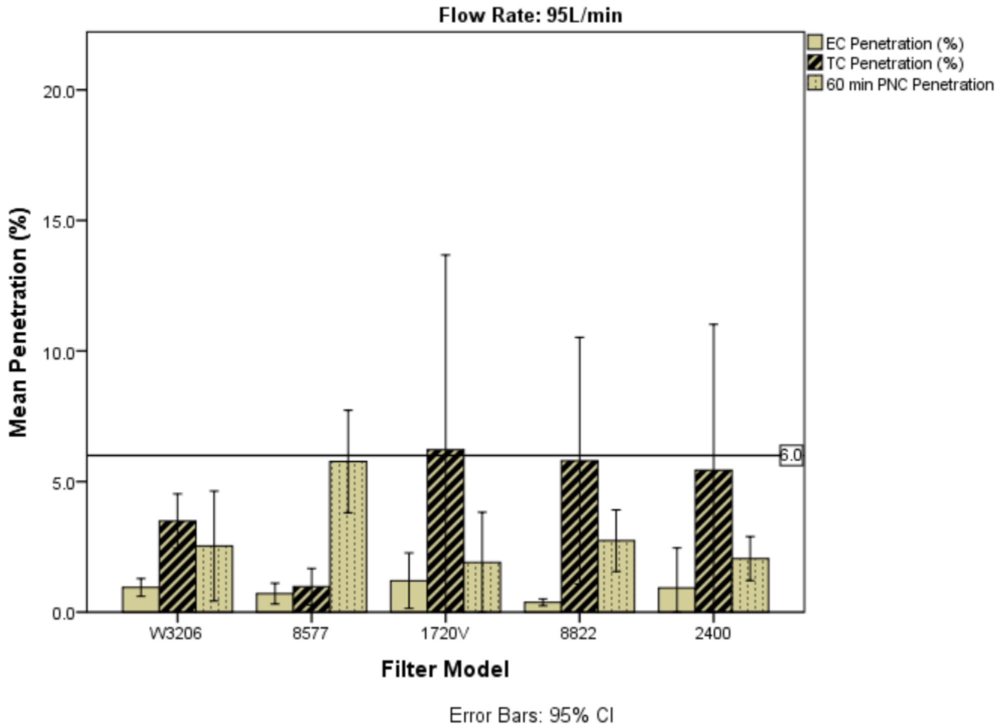

Figure 4-2: Effect of Filter Model and Flow Rate on EC, TC and PNC Penetration at 95L/min, Mean ± 95% Confidence Interval, n = 6-9, Reference Line represents 6% Penetration

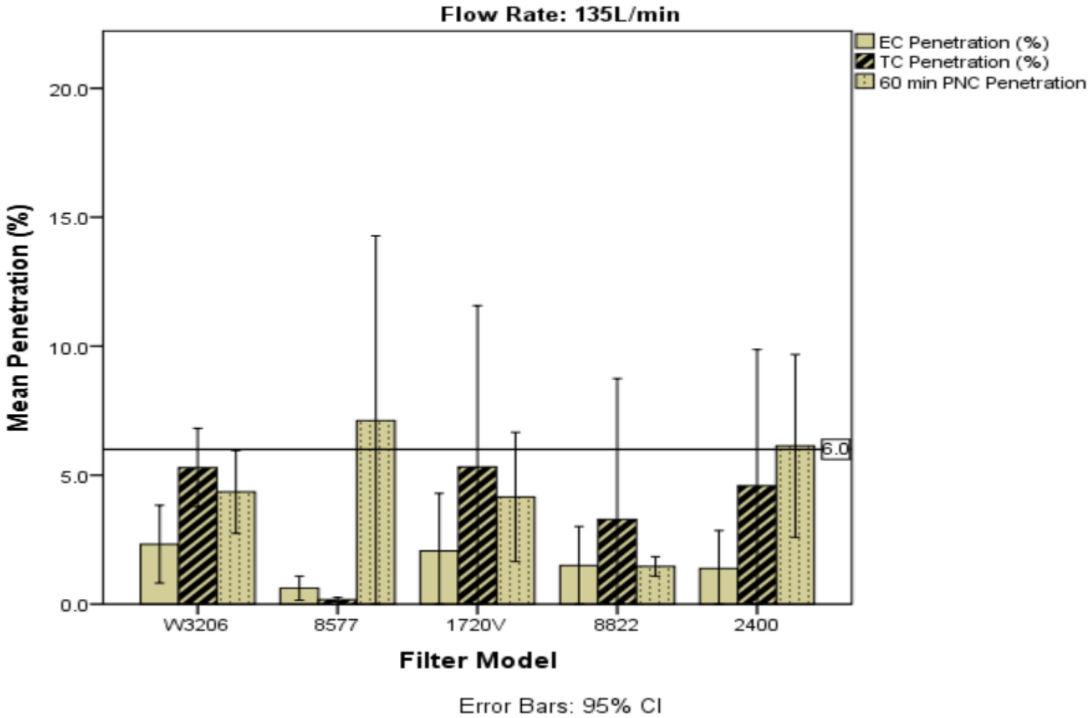

Figure 4-3: Effect of Filter Model and Flow Rate on EC, TC and PNC Penetration at 135L/min, Mean ± 95% Confidence Interval, n = 6-9, Reference Line represents 6% Penetration

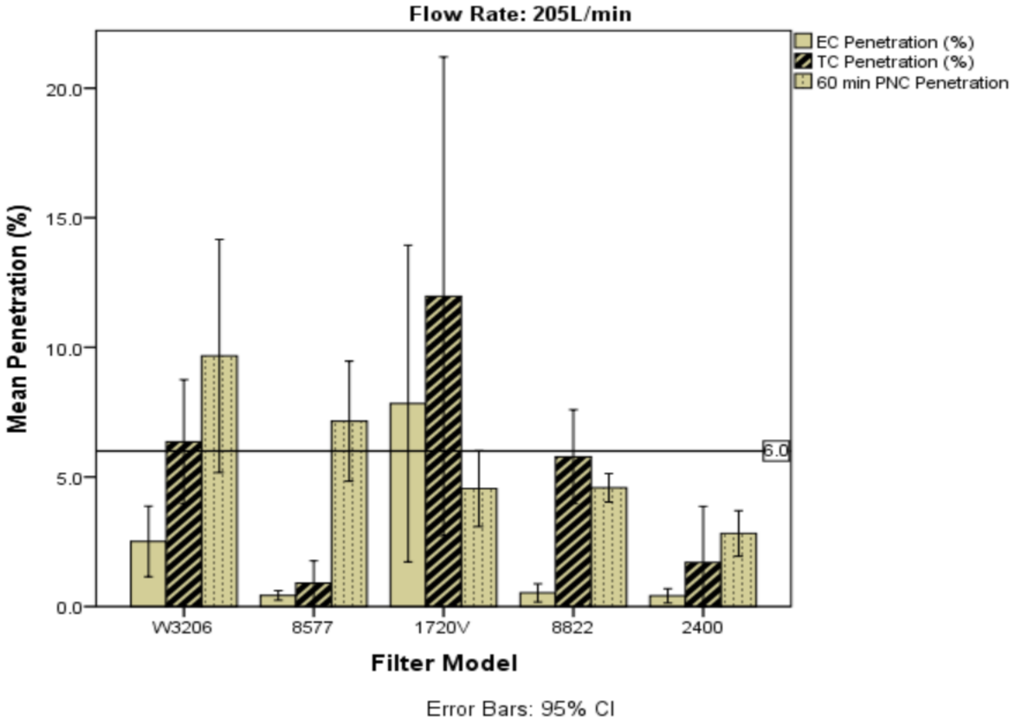

Figure 4-4: Effect of Filter Model and Flow Rate on EC, TC and PNC Penetration at 205L/min, Mean ± 95% Confidence Interval, n = 6-9, Reference Line represents 6% Penetration

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

Penetration by particle number was recorded every 15 minutes over the one hour sampling period. When sample time was compared by a OneWay ANOVA for all results obtained in the study, the results between each sample period were not significantly different $F(4,466) = 1.41$, $p=0.230$.

4.6 Results of Filter Testing by External Laboratory

A batch of 8822 filters were sent to an external laboratory to enable comparison of the results obtained from testing with the standards specified challenge aerosols with the findings from the study, the results are reported in Table 4.7. The testing was conducted at a flow rate of 95L/min.

Table 4.7: 8822 TEST results using standard specified challenge aerosols

	NaCl				**Paraffin Oil**			
	M	***SD***	***n***	***UCL***	***M***	***SD***	***n***	***UCL***
Penetration after 3 min (%)	0.64	0.30	8	0.90	1.55	0.30	8	1.80
Maximum Penetration (%)	0.70	0.31	8	0.95	2.28	0.47	8	2.68

The results from external laboratory testing were compared by One Way ANOVA with the EC, TC and PNC results for the 8822V filter at 95L/min obtained in this study. The results were significantly different using the Welch test as equal variances were not assumed ($F(7,19)=27.56$, $p<0.001$). Post-hoc tests were conducted using a Games-Howell test. Interestingly, the results for NaCl max and 3 min were significantly different from the Paraffin Oil Max and 3 min tests. EC penetration was also significantly different to both Paraffin Oil tests and the 60minute PNC penetration results.

The comparison for these results and challenge aerosols is displayed in Figure 4.5.

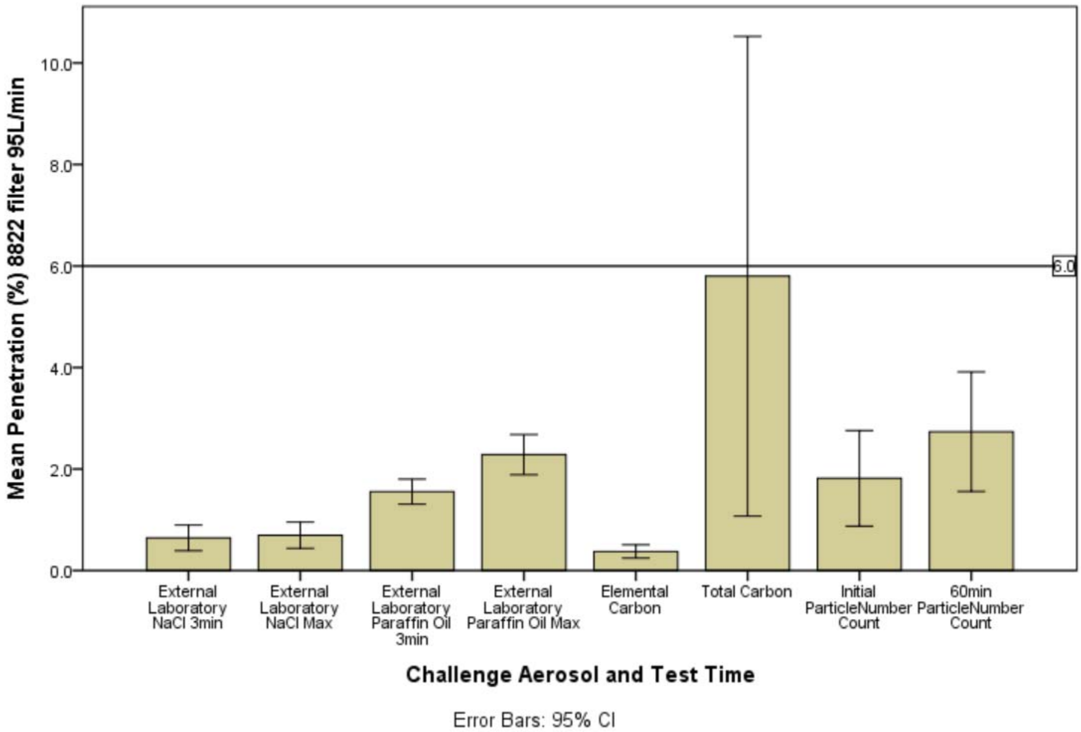

Figure 4-5: Effect of Challenge Aerosol and Sample Time on Penetration Results, Mean ± 95% Confidence Interval, n = 6, Reference Line represents 6% Penetration. Paraffin Oil and NaCl were tested by the external laboratory, EC, TC and PNC were tested during the study.

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5. Discussion and Conclusion

5.1 Key Findings

5.1.1 DPM Penetration at Standard Designated Flow Rate measured by EC and TC

Research Question: Does standards certified P2 respirator filter media used in Australian workplaces effectively filter out DPM, when challenged with emissions from a diesel engine and measured as penetration of EC and TC through the respirator filter media?

To evaluate this question, the filters were tested with the diesel emissions as the challenge aerosol, in place of NaCl. The concentration of the challenge aerosol was set at 1mg/m3 EC, which is at the upper end of the exposures reported in workplace studies, and the rated protection factor for the P2 filters.

EC penetration was below the standards certification requirement of 6% for all filter models combined and each individual filter model for both mean and 95%UCL penetration. TC penetration results for all filter models except the 1720V were below 6% mean penetration, however the 95%UCL result exceeded 6% for 1720V, 8822 and 2400. The variability in TC penetrations is due to the variability in Organic Carbon (OC) results measured throughout the sampling period.

Therefore the findings indicate that penetration is below 6% for all of the filter models, when measured as EC penetration through the filter media and for two of the five filter models, when measured as TC penetration, at the standard specified flow rate of 95L/min.

5.1.2 DPM Penetration at Standard Designated Flow Rate measured by Particle Number Count

Research Question 2: Does standards certified P2 respirator filter media used in Australian workplaces effectively filter out DPM, when challenged with emissions from a diesel engine and measured as penetration by PNC?

Penetration measured as PNC was below 6% for all filters combined and for each individual filter model, with the exception of the 8577 filter which slightly exceeded this result for the 95%UCL.

Therefore, the findings indicate that filtering efficiency is below 6% PNC penetration for four of the five filter models, at a flow rate of 95L/min.

5.1.3 DPM Penetration at flow rates representative of moderate to heavy work

Research Question 3: Does Standards Australia certified respirator filter media effectively filter out DPM at flow rates representative of moderate to heavy work rates, measured as penetration of EC, TC and PNC at 135 and 205L/min?

At 135 and 205L/min, EC penetration was below 6% for all filter models, with the exception of the 1720V filter 95%UCL at 205L/min. For TC, mean penetration was at or below 6% for all filter models at 135L/min but the 95%UCL was exceeded for four of the five filter models. At 205L/min mean TC penetration exceeded 6% for two of the five filter models and for three of the five when the 95%UCL was considered. Initial PNC penetration at 135L/min was below 6% for three of the filter models, two of which remained below 6% penetration after 1 hour of exposure. At a flow rate of 205L/min through the respirator filter three filter models were at or below 6% penetration, both initially and after 60 minutes of exposure to the diesel engine emissions.

Therefore, the findings indicate that for the respirator filter models, EC was effectively filtered out at 135 and 205L/min with the exception of one filter model at the higher flow rate. TC was filtered out effectively for all but one filter model at 135L/min and for two filter models at 205L/min. Particles were effectively filtered out for three of the five filter models, at flow rates of 135 and 205L/min.

These findings are consistent with studies using various challenge aerosols that have also reported penetration increases as flow rate increases (Balazy et al. 2006; Eshbaugh et al. 2009).

5.1.4 Comparison of Test Methods

Research Question 4: 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 newly adopted AS ISO 16900.3 (Standards Australia Limited 2015) adequately assess whether P2 certified respirator filter media effectively filters out DPM.

Results from comparison of the various challenge aerosols and testing times, although limited to one filter model and flow rate, showed a statistically significant difference between mean penetration for NaCl [M=0.6, SD = 0.3] and Paraffin Oil [M=2.3, SD=0.5]. The difference in mean penetration was statistically significant between PNC after 60 minutes [M=2.7, SD=3.9] and EC, as was the difference between EC [M=0.4, SD=0.1] and Paraffin oil.

Therefore, results from external laboratory testing using standard challenge aerosols show that Paraffin Oil is a more conservative test than NaCl. 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 respirator filter without replacement. 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.

5.1.5 Effect of Respirator Filter Model on DPM Penetration

The specific respirator filter model was found to have a significant impact on measured EC, TC and PNC penetration through the respirator filters. The finding that measured penetration varies with filter model is not unexpected as filter media vary in design properties, which use different mechanisms of particle capture, as described in Section 2.4.4. The respirator filter models used in the study differ in filter capture design properties some being electret type filters, and others a combination of mechanical and electret properties.

The US NIOSH standard recognises different challenge aerosols will have differing effects on respirator filter media, incorporating a rating scheme which distinguishes between oil based and non-oil based contaminants. In the specific case of DPM, a US research study found that penetration did not meet certification requirements for N rated filter media, however the criteria were met for P and R rated filters (Janssen & Bidwell 2006), when measured at a flow rate lower than that specified in the standard. European Standards specify penetration tests for particle filters using both NaCl and Paraffin Oil. In Australia there is no distinction between the types of aerosol that the filter is rated for, other than mechanically generated compared with thermally generated particles, and the protocol specifies NaCl for filter penetration tests.

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

5.1.6 Effect of Increased Flow Rate on measured Penetration

Flow rate through the respirator filter was found to have a significant effect on filter penetration for EC, TC and PNC penetration for some filter models. Post hoc analyses generally found that the results were significantly different between 95 and 205L/min as well as 135 and 205L/min..

Recognition of the importance of considering work rate in the selection of appropriate respiratory protection, and subsequent certification testing at these work rates, is being incorporated into the updated ISO Performance Standard (ISO 2013). The Draft ISO Performance Standard proposed four work rate classes, with the test specification varying with testing for Work Rate 1 to be conducted at the flow rate of 85L/min, Work Rate 2 at 135 L/min, Work Rate 3 at 205L/min and Work Rate 4 at 255L/min.

Adoption of the ISO Performance Standard by Standards Australia will require manufacturers and suppliers to incorporate these new requirements into certification testing regimes and filter ratings. Respirator users will also be required to consider work rate when they select the appropriate respirator filter.

These findings indicate that it may be possible to streamline certification testing protocols by conducting tests at only two of the three flow rates, which would be a cost benefit to respirator manufacturers and ultimately respirator users, should this ISO standard be adopted for Australian workplaces.

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 the experimental findings indicating that measured penetrations increase at the higher flow rate.

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 (Burton et al. 2016; Janssen 2003). 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 may provide a more conservative estimate of exposure to DPM than NaCl and hence be more protective of worker health.

5.3 Study Limitations

It is well documented that diesel exhaust emissions vary in characteristics based on variables such as engine size, 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 0.7 measured for this study, therefore the results would be consistent for those seen in Australian industries and workplaces that may require respiratory protection.

Whilst consistent engine load settings were used, a slightly higher than desired pre filter concentration occurred. The lack of instantaneous sampling results meant that required methodological adjustments, such as reducing the pre filter EC concentration, were not apparent until the results were received after the sampling was complete.

5.4 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. Furthermore, certification testing is not conducted at flow rates representative of moderate to heavy work, despite indications of increased filter penetration with increasing flow rate. These findings have implications for workers required to wear respiratory protection, particularly those who are required to work at moderate to heavy work rates.

This research will assist the development of improved Australian and International standards relating to the selection and evaluation of DPM respiratory protection equipment, so as to better manage the health risk for personnel exposed to this workplace carcinogen. In particular, 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 that consideration be given to mandating the use of Paraffin Oil as the challenge aerosol, rather than alternative, given this was a more conservative measure in this study and is consistent with US 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 selection of respirator filters for use against DPM.

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