UNIVERSITY OF WOLLONGONG

Faculty of Science, Medicine and Health

COAL SERVICES HEATH & SAFETY TRUST RESEARCH PROJECT

Calibration of Portable Raw Exhaust Diesel Particulate Analysers

Final Report – 2 August 2013

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2 August 2013

EXECUTIVE SUMMARY

The aim of this research project was to develop a practical means by which portable diesel particulate analysers used in the underground coal mining industry to measure raw exhaust diesel particulate (DP) levels could be calibrated to an internationally accepted standard used for health assessment. As a result of the research conducted and detailed in this report, the following outcomes have been achieved.

It is possible to use a small diesel generator to produce an exhaust stream that provides varying levels of elemental carbon (EC) at different engine loads with a reasonably even distribution across the exhaust pipe. This then provides a valuable means for the calibration of instrumentation directly to NIOSH method 5040 which is an internationally recognised standard for health assessment.

The use of laser light scattering (LLS) instruments with generic factors to convert the measured total particulate matter (TPM) to EC is only valid for the types of engines that they were originally derived. On this basis every new type of engine that enters underground diesel fleets in coal mines should be evaluated to establish if the current factor remains appropriate. If this occurs, direct reading instrumentation (eg LLS) should provide a useful means for the quick measurement of raw exhaust EC. If the industry does not wish to undertake this work then TPM may be a possible metric for the estimation of raw exhaust DP however clarification of the variation in correlation issues raised by Vouitsis, Ntziachristos & Samara (2003) and the NSW Department of Primary Industries report (NSW 2004) will be required before this alternate metric could be used on all engines in current diesel fleets. In either case, checks at appropriate intervals by other potentially slower means would add significantly to the confidence of results obtained by LLS.

The sampling of raw exhaust DP using quartz filters for subsequent EC analysis is a viable alternative to current technologies however the process does not lend itself to sampling post a water-filled scrubber tank or for the provision of instant results. It does however provide an excellent audit or checking method for direct reading instrumentation.

The Freudenberg sampling system appears to be suitable for the collection of raw exhaust for subsequent EC analysis as a check method for LLS devices provided a number of modifications to the tested prototype recommended to the manufacturer are implemented.

The depth that a probe is inserted into the raw exhaust of an engine can have an effect on the concentration of EC measured. This may be a factor in the high level of variability of results experienced by mines when using different testing organisations. For the engine used in this project a probe of 21 cm appears appropriate.

No effect on raw exhaust EC concentration caused by temperature was observed when sampling the raw exhaust at approximately 115^{o}C compared to that at 45^{o}C. This is a significant finding as it allows the gas sampling point on the manifold of underground diesel engines used in the coal industry to be the place of choice to collect samples. This should have a major effect on minimising sampling errors provided the exhaust is appropriately cooled and mixed.

The device developed by Emission Reduction Products Engineering Pty Ltd (ERP) to collect a suitable sample from the gas sampling point appears to work, but further evaluation is required over a range of in-service vehicles.

Arising from the above outcomes the following recommendations are put forward for consideration by the coal industry.

If LLS devices are to be used for the measurement of raw exhaust EC the coal industry needs to establish the elemental carbon to total carbon (EC/TC) ratios for new generation engines so that more accurate results for raw exhaust monitoring of these types of engines can be obtained when using direct reading instrumentation. To do this a detailed study of a range of equipment needs to be undertaken which could be progressed in concert with the evaluation of monitoring from the gas sampling point, rather that the currently used exhaust pipe. Longer term, all new engines should have their EC/TC ratio established at the certification stage in a manner consistent with how the engine will be tested when in-service.

If TPM is chosen as the preferred measured metric, LLS TPM versus standard method TPM correlations (mass and size fraction) for all newer design engines in service (i.e. introduced post 2002) should be determined. Longer term, this could be established at the certification stage in a manner consistent with how the engine will be tested when in-service.

Irrespective of the metric used a standard method for the sampling of raw exhaust for DP needs to be implemented by the industry. The current monitoring approach does not detail probe insertion distance, probe type or any requirements for the calibration of measurement instrumentation to an internationally accepted standard. Any such standard method should be developed with the input of all stakeholders so that one single approach is adopted by the industry.

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Computer aided diagram of exhaust system

1. INTRODUCTION

Following an extensive investigation in 2004 by the NSW Department of Primary Industries (NSW 2004) a number of measurement techniques including laser light scattering instrumentation (LLS) were identified as being capable of measuring diesel particulate matter (DP) in the raw exhaust of diesel engines used in the coal industry, albeit with some caveats.

Over the intervening years since 2004 to the present time, LLS instrumentation has evolved to be the measurement technique of choice within the industry due in part to the desire to have instant results and the potential for one person operation. Historically however, there have been reports of instances where significant variability in results obtained from different types of instruments, or in some cases the same type of instrument. Subsequent investigations have not been reported establishing if these variations arise from the instrument themselves or sampling issues. Irrespective of the source any major variability in results leads to confusion amongst mine engineers when deciding appropriate maintenance strategies to control exhaust emissions and thus the use of emissions based maintenance programmes (which depend on knowing the raw exhaust DP concentration) are in many cases not being implemented at the level they should be to provide an effective control strategy for worker exposure.

One of the fundamental principles of measurement of any parameter is the process of calibrating the analysis method or measurement instrument to an acceptable standard. Investigation of the calibration of the LLS instrumentation used in the coal industry indicates that they are calibrated to TPM (which is consistent with international standards) and then a correlation factor is applied to convert the measured reading to EC. If the desired outcome is to have results reported in EC then it would appropriate to calibrate LLS instruments directly against EC.

For a number of years NIOSH method 5040 (NIOSH 1994) has been the method of choice to evaluate worker exposure to atmospheric concentrations of DP and if raw exhaust EC results are subsequently used to develop control strategies for mitigating workplace exposures (e.g. ventilation design) it is appropriate to use EC for the calibration of instrumentation providing those results.

This project aims to develop a practical means by which portable diesel particulate analysers could be calibrated to EC using NIOSH method 5040. The following sections detail the results of the investigations conducted so as to achieve this outcome.

2. LITERATURE REVIEW

A literature search targeted at DP generation and sampling systems was undertaken prior to the submission of the grant application to the Coal Services Health & Safety Trust and a summary of that exercise is provided below.

An excellent review of techniques to measure particulate in the raw exhaust of diesel engines is provided by Burtscher (2001). Burtscher (2001) states that as new technology engines become available the traditional method of determining particulate emissions on a mass basis is not adequate due mainly to the massive reduction in particulate mass from newer generation engines placing gravimetric analysis at the limit of its detection. Burtscher (2001) also states that there is a dominance of the volatile fraction over the mass fraction in these engines and this would make any gravimetric measurement technique unstable and thus unreliable. Burtscher (2001) recommends that the solid fraction could best be measured by using EC as a surrogate and goes onto indicate several techniques that potentially could be used.

This statement is sensible as current practice is to assess worker exposure to DP by measuring EC using NIOSH method 5040 (NIOSH 1994). Similarly, if raw exhaust EC can be accurately measured it should be possible to estimate the quantity of ventilation required so as to dilute the exhaust emissions below the generally agreed workplace exposure standard of 0.1 mg/m^3 (AIOH 2013).

Other work has shown a relatively good relationship between diesel particulate matter measured gravimetrically and other measurement technologies such as LLS (NSW 2004; Snelling et all 1999; Schrami, Will & Leipertz 1999) however high soluble organic fractions were cited as interference in some cases. Vouitsis, Ntziachristos & Samara (2003) indicated that LLS provided a simple, low-priced technique free from non-particulate interferences which is not consistent with the statements of Snelling et all 1999; Schrami, Will & Leipertz 1999. One significant finding of Vouitsis, Ntziachristos & Samara (2003) was that the correlation of LLS measured TPM to TPM measured by mass (the standard method) changed for different operating conditions and engine types. This finding is also discussed in the NSW Department of Primary Industries report (NSW 2004) where a similar effect was discovered in relation to Caterpillar 3126 engines.

Irrespective of what technique is used for analysis of raw exhaust DP any calibration process requires a means of producing a steady flow of diesel exhaust. Traditionally there have been two approaches to the collection of DP these being a partial flow sampling system (PFSS) or the full flow constant volume sampling (CVS) technique. CVS is the standard method for collecting exhaust particulate under transient engine operation (Khalek et al 2002; US EPA 2013). The CVS system is expensive and requires large facilities and does not lend itself readily to the routine calibration of portable instruments.

A CVS system was used by the NSW Department of Primary Industries in 2004 (NSW 2004) to establish suitable instrumentation for the measurement of raw exhaust DP from diesel vehicles at underground coal mines. This was supplemented by an extensive field trial and is by far the most comprehensive study of its type in the Australian coal industry to date. A summary of the key outcomes of this project can be found in section 3.3.

For many years researchers have been searching for a “real world” option to CVS systems which are laboratory based and expensive. Mini (Divis &

Tichanek 2002) and micro (Cirillo 2001) dilution tunnels have been developed however all have limitations so their use requires an understanding of potential errors. If the aim is to achieve a relatively stable supply of raw engine exhaust that does not necessarily meet certification requirements then such approaches have value.

One such approach was undertaken by Dahmann (1997) and his work indicated that it was possible to use a relatively small dilution system to provide an exhaust where EC concentrations could be measured to enable the comparison of different sampling techniques. Miller, Habjan & Park (2007) took a different approach and used a 1.5 litre diesel engine linked directly to a large multiport sampling chamber (with no mixing) to measure real time EC levels for the source engine and compare these to NIOSH method 5040 (NIOSH 1994).

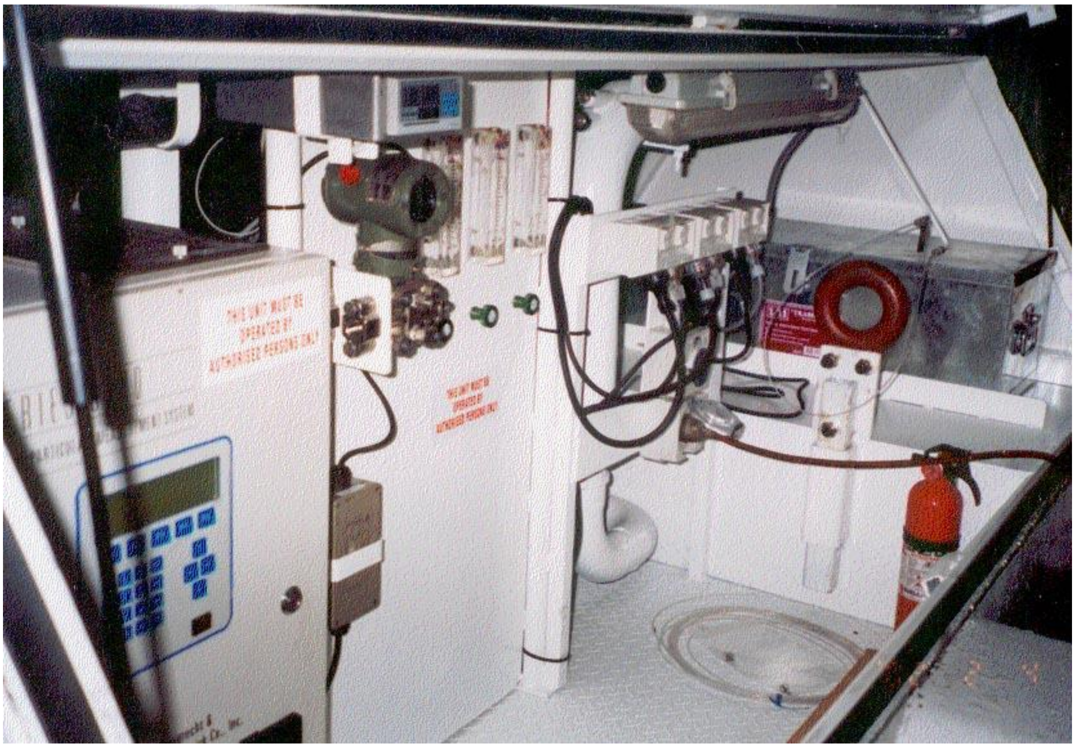
The targeted literature review indicated that there had been attempts to find a technique to produce DP for the calibration or evaluation of monitoring techniques that would provide a non-laboratory based option to CVS systems albeit with inherent limitations. It is also apparent from the literature that the traditional method of comparison to gravimetric sampling is becoming more difficult as engine particulate levels decrease with newer generation engine technology. At this point in time the use of raw exhaust EC as the measurement surrogate is considered appropriate by health professionals as it allows potential linkage to control technology design (e.g. ventilation) and thus ambient worker exposure levels.

3. HISTORY OF RAW EXHAUST DP MONITORING IN THE AUSTRALIAN COAL INDUSTRY

3.1 Tower Colliery project

The Tower Colliery project (Pratt et al 1997) was the largest and most in-depth scientific study of diesel particulate in the Australian coal industry if not the world at that time. It took place from August 1990 until April 1993 and amongst other findings clearly linked exhaust DP levels to maintenance and ventilation. While measurement techniques were in their infancy for the assessment of ambient DP levels at that stage, little thought had been given to raw exhaust DP monitoring even though monitoring for raw exhaust gases was well defined and implemented across the industry.

As the findings of the Tower Colliery project were progressively rolled out across BHP Steel Division Collieries (the funding organisation of the Tower Colliery Project) it became increasingly clear that having information on the raw exhaust DP concentration would be very useful especially in ventilation design applications. To this end a research grant was sourced from the Australian Coal Association Research Programme (ACARP) in the late 1990’s to use a laboratory elemental carbon analyser (R & P 5100) mounted in a trailer (ACARP 2000) so as to measure the raw exhaust elemental carbon levels of in service mine vehicles Figure 3.1.



Source: B Davies

Figure 3.1 - Elemental carbon analyser for raw exhaust analysis

This unit remained in service for approximately ten years until the manufacturer was purchased by another instrument company and spare parts and consumables became unavailable.

What this instrument did was demonstrate the value of measuring raw exhaust DP levels and subsequent work with this unit (Davies 2004) demonstrated how the use of raw exhaust DP analysis (as EC) could be used in targeted maintenance programmes to reduce employee exposure and boost productivity. Table 3.1 demonstrates how simple maintenance procedures can significantly reduce raw exhaust EC levels and thus worker exposure.

Table 3.1 - Effect of maintenance on raw exhaust EC concentration

Vehicle	Pre Maintenance Raw Exhaust EC mg/m^3	Post Maintenance Raw Exhaust EC mg/m^3	Maintenance Performed
PJB A	139	46	New fuel pump and cleaned scrubber tank
PJB B	131	40	New scrubber tank, new injectors & fuel adjustment
PJB C	102	61	New injectors, cleaned scrubber tank & air intake filter
Ram Car	159	71	New injectors

Source: B Davies

3.2 NIOSH project

In 2000 a chance discussion between the author and Dr Jon Volkwein of the National Institute of Occupational Safety & Health (NIOSH) lead to a device he had been developing for dust levels on long walls being converted to the measurement of raw exhaust DP levels. The device was based on the principle that there would be an increase in back pressure when a known volume of diesel exhaust was collected on a filter. The device (Figure 3.2) was calibrated against NIOSH method 5040 and trialled in Australian, South African and USA mines (Volkwein et al 2008).

Source: B Davies

Figure 3.2 - NIOSH DP Instrument

While this device was simple to use it depended on having a constant supply of filters with very small pressure tolerances which was found to be commercially unsustainable and the instrument never progressed from the prototype stage to commercial production. The device was however used in a major Australian study on instrumentation for raw exhaust monitoring the results of which are reported in section 3.3.

3.3 Coal Services Health & Safety Trust project

The most comprehensive evaluation of techniques for the measurement of DP in the raw exhaust of diesel engines in the coal industry was undertaken by the NSW Department of Primary Industries (Mines Safety Technical Services) in the period 2002 to 2004 (NSW 2004). This extensive project was funded by the Coal Services Health & Safety Trust and was the first scientific attempt within the coal industry to evaluate all available technologies so as to find one or more methods for measuring DP in the raw exhaust of diesel-powered mining equipment at underground coal mines.

To be an acceptable measurement method it was required to correlate reasonably well with the standard gravimetric method for measuring DP at that time (US EPA Method Title 40 Protection of Environment, Part 1065) and also be practical for use underground at mine sites by mine personnel.

The selection criteria for techniques to be included in this project are listed in Table 3.2.

Table 3.2 – Selection criteria for instruments to evaluate

Selection criteria	Priority	Comments
Available, supported by supplier	2	Problems may exist with a local supplier, but can often 'get around' such problems; need technical specifications for any proposed instruments
Suitable for use by mine personnel	1	The proposal is that mines have the measuring instrument and do the measuring themselves.
Price within budget for project, and reasonably priced for mines	1	As a guide only, the project proposal included 4 instruments at A$15,000 each.
Suitable for sampling before and after water scrubber	2	Not known if this would be possible.
If possible consistent with what others are using	2	Other agencies are asking questions similar to that of this project; eg RTA in NSW, NEPC – National Environmental Protection Council
Suitable for use underground	1	
Suitable for use in hazardous zone	2	
Response time	1	Quick enough to avoid overloading engine during test.
Portable, hand held	1 or 2	
Adequate information available on the instrument	1	Such as accuracy, precision, repeatability
Ability to calibrate	1	
Suitable measurement range	1	
Suitable particle size range	1	
Able to sample transients during acceleration	2	The increasing use of turbo-charged engines makes this desirable.

Source: DPI (2004)

After evaluating the techniques the researches decided to trial three LLS instruments and the NIOSH back pressure method (section 3.2) against gravimetric filter analysis of total particulate matter (TPM), a tapered element oscillating microbalance (TEOM), a Bosch smoke meter (partial tests only) and the R & P 5100 technique (section 3.1) used in the Tower Colliery project.

The conclusions from this project were that one of the LLS devices (AQT DPM) fitted with a dilution and drying unit and the NIOSH device were suitable instruments for measuring DP from the raw exhaust but both had limitations.

The report also states that newer generation engines (Cat 3126 at that time) gave a totally different response when sampled by LLS instruments and the R & P 5100 against TPM and EC but not with the NIOSH pressure drop device which was relatively consistent across all engine types.

In regards to the calibration of LLS instruments the report also states that the instruments were calibrated by their suppliers and that this aspect had not been investigated nor did the research team have any information on the consistency of individual supplier calibrations. In hind sight it would have been prudent to investigate this area more fully however as the researchers only recommended this instrumentation be used for the comparison of engines within each engine type to weed out high emitting engines, absolute calibration wasn't necessary provided the same instrument was used for the comparison. The report specifically states that the instrumentation of the time was not suitable for the setting of a standard for DP emissions from all engine types. This is a major point that has been overlooked in the development and application of this style of instrumentation since the early trials of this project.

This project still remains the core knowledge as to the use of direct reading instrumentation to measure DP in the raw exhaust of diesel engines in the coal industry, however many of its findings have not been fully investigated or correctly interpreted in the rush to find a relatively simple measurement tool.

The current research project has investigated a number of issues that were identified in the (NSW 2004) report, the findings of which are provide in following sections.

3.4 Issues with routine monitoring at mines

Since 2004 routine monitoring of raw DP has increased across the industry with various technologies being developed. The most common approach has been the use of LLS instrumentation using sample dilution and drying. As previously stated the R & P 5100 is no longer supported by the new owner of the original manufacturer and the NIOSH pressure drop device never proceeded to commercialisation mainly due to the lack of a filter with a reproducible pressure drop.

While there has been substantial progress on the instrumentation aspect there has been little progress on the important aspect of calibration of this instrumentation especially in terms of EC which is the value that is routinely reported to mine engineers. The focus of calibration to date has been the use of mass based methods to calibrate LLS devices against TPM which has shown good results but with some reports such as Vouitsis, Ntziachristos & Samara (2003) indicating different correlations with engine types and loads. The LLS device is used to measure the raw exhaust TPM and then a correlation factor supplied by the manufacturer is then used to convert the measured TPM to raw exhaust EC.

Discussions with a number of mine site and testing personnel have resulted in expressions of frustration at the lack of consistency in raw exhaust DP monitoring. The author was made aware of cases where two different testing organisations tested the same engines and reported significantly different results even though the testing was only days apart. It is totally inappropriate to state that the instrumentation itself is the only possible source of error in such cases as aspects such as sample probe location, engine load and operator technique also play a major role in such differences.

The NSW Department of Primary Industries guideline (MDG 29 2008) contains a number of sections covering the sampling of the raw exhaust of diesel engines for DP and adherence to the procedures indicated should minimise any errors in engine load (but not totally eliminate them in all cases). As the industry moves to newer design engines there is a need to ensure that current engine load techniques cover these engines or are modified where appropriate.

Sampling from the raw exhaust of diesel engines post a water-filled scrubber always complicates the process due to the large volume of water droplets and water vapour introduced into the gas stream. Over the last ten years there has been a default approach to sample raw exhaust DP after the water filled scrubber tank most probably due to the fact that the raw exhaust is only accessible at this position and the gas sampling point on the engine manifold. As disposable exhaust filter canister design has progressed, the ease of obtaining access to the whole raw exhaust post the scrubber tank and filter canister (without a filter fitted) has become increasingly difficult and could be one of the major reasons for analysis variations. To overcome this problem and gain consistency in the sample collection process the gas sampling point potentially offers more opportunity provided that the exhaust temperature can be quickly reduced and good mixing is obtained.

It is clear that a standard sampling approach that minimises all known errors must be adopted by the industry if the variations in results that have occurred in the past are to be minimised.

4. DESIGN OF DIESEL PARTICULATE GENERATOR

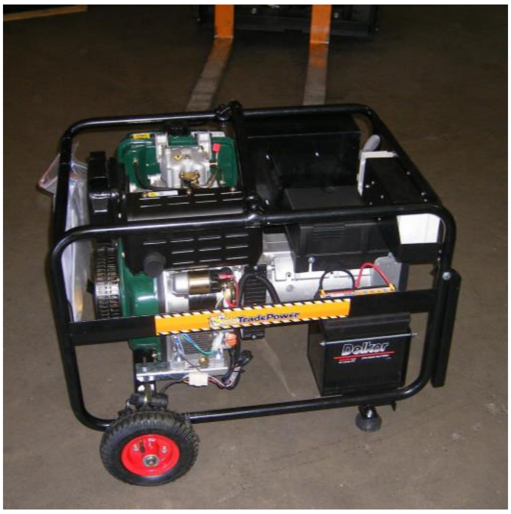
4.1 Selection of base generator

As discussed in section 2, the research of Dahmann (1997) showed that it was possible to obtain reasonably consistent raw exhaust EC concentrations from a 45 kW engine using a miniature dilution tunnel. The aim of the current project was to build on this work and design a system where the engine raw exhaust was mixed to give a consistent EC concentration across the exhaust pipe in the minimum distance possible from the manifold to the exhaust outlet.

Key to this process was having a much smaller diesel engine than that of Dahmann (1997) that could produce the required EC but also link this to a generator so that varying power loads could be placed on the generator to make it work harder thus producing varying levels of EC in the raw exhaust. If successful, this simple basic concept would provide the means by where varying concentrations of EC could be effectively produced when required for the subsequent calibration of instrumentation.

A review of the information available from portable diesel generator suppliers highlighted that the general approach was to rate the engine such that the maximum efficiency was achieved when the engine was under power loads in excess of 50% of the stated output. This meant that the engine could be very basic with a simple constant fuel supply throttle which resulted in over-fuelling at low engine loads and better fuel to air mixtures under high loads. All systems on the market were similar and thus a 6 kVA portable power generator powered by a one cylinder air cooled diesel engine was selected (Figure 4.1). The original unit was modified by the supplier to provide dual 240 V power outlets, a rev counter and power over load circuit breaker (Figures 4.2 & 4.3).

All testing throughout the duration of the project was conducted using Shell Ultra Low Sulphur diesel fuel of approximately 10 ppm sulphur (Shell 2013) as this is the type of diesel fuel used by the majority of coal mines.



Source: B Davies

Figure 4.1 - Diesel Generator

Source: B Davies

Figure 4.2 - Power Outlets

Source: B Davies

Figure 4.3 - Rev Counter

4.2 Design of exhaust mixing system

The research of Dahmann (1997) showed that it was possible to produce a stable supply of raw exhaust with EC concentrations reasonably consistent across the exhaust from a small engine. The difficulty was that the overall length of the miniature dilution tunnel was approximately 22 metres which was impractical for use in the situation envisaged. Consequently the challenge was to design a system that produced a supply of raw exhaust DP with good consistency across the exhaust pipe albeit with the understanding that such a considerable miniaturisation would result in dilution errors. Such errors were not considered important provided the exhaust DP concentrations across the exhaust pipe were reasonably consistent across the exhaust pipe (section 5.3).

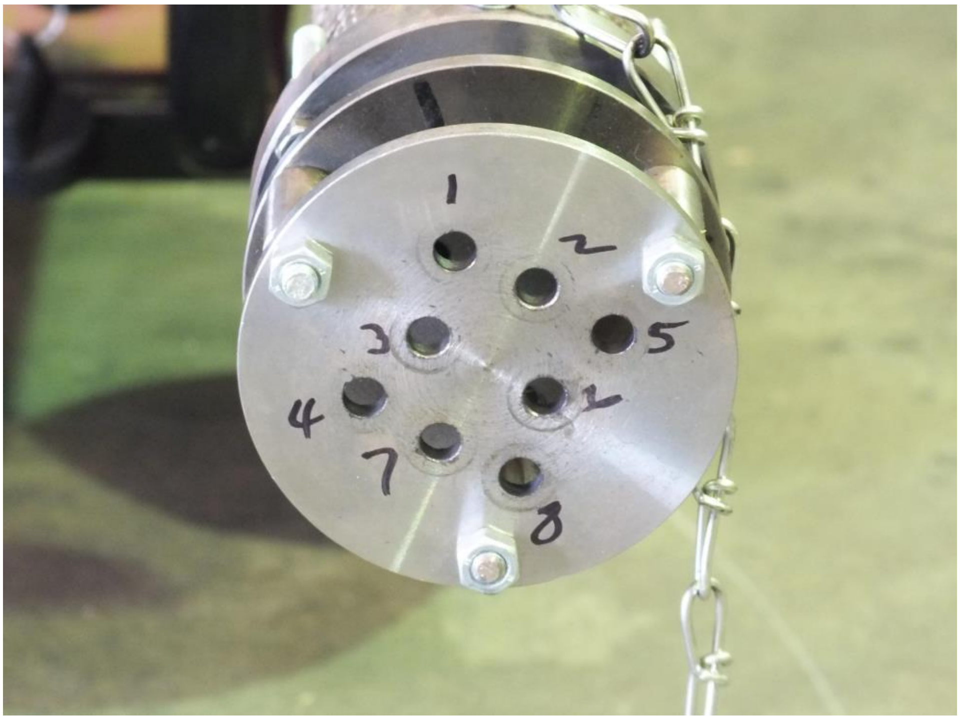
An engineering company (ERP) were contracted to design such a system in consultation with the author. The design (see Appendix) consists of a plenum (also acts as a muffler) and a mixing chamber. The mixing chamber was designed so that the raw exhaust coming from the engine is split and one part forced down the outside of an inner concentric pipe so as to maintain the inner pipe wall temperature and the other part of the exhaust passed through the inner pipe via a mixer to the atmosphere. The amount of exhaust passing over the inner pipe could be controlled via a ball valve if required. All hot surfaces were lagged where possible so as to minimise heat loss.

A cover was fitted to the unit so as to minimise noise from the engine as it was deemed excessive. The overall system is illustrated in Figure 4.4.

Source: B Davies

Figure 4.4 - DP generator with exhaust mixing system

In order to measure the raw exhaust DP concentration across the face of the exhaust it was considered necessary to have a means by which the probe could be inserted into the exhaust at the same point on repeated occasions. ERP designed and constructed a probe location system that achieved this requirement by the use of duplicate plates drilled to accept the probe separated by spacers (Figure 4.5).



Source: B Davies

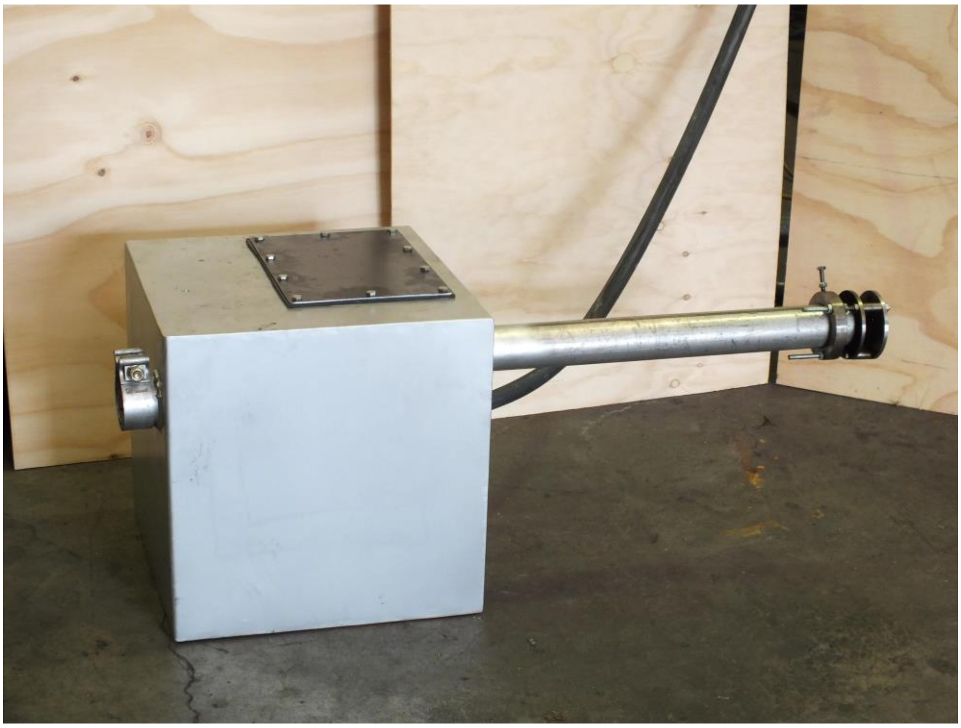
Figure 4.5 – Probe locator device

Initial testing of the system showed all components to work well and to design expectation except the noise cover. In order to reduce the noise levels emitted from the engine further enclosure of parts was attempted however this resulted in increased temperatures within the engine compartment and was removed. As the task was to produce a system for proof of concept and not for commercial production the alternative approach of enclosing the whole DP generation system inside an open top noise barrier (Figure 4.6) was evaluated with a resultant substantial reduction in noise levels from 102 dbA to 85 dbA. It is clear any long term use of such a diesel particulate generator system would require more practicable noise control measures than those used in this research situation.

In order to make the system as similar as possible to those in operation a scaled down water-filled scrubber tank was constructed (Figure 4.7). The scrubber had a constant flow header tank and the scrubber unit could be added to or removed from the exhaust pipe of the DP generator when desired. This provided an easy means of sampling the raw exhaust pre or post the scrubber when appropriate.

Source: B Davies

Figure 4.6 – Noise barrier around DP generator



Source: B Davies

Figure 4.7 – Water-filled scrubber tank

4.3 Design of the sample collection system

As the intended approach was to calibrate the direct reading LLS instruments using an international standard method (NIOSH 1994), measures must be taken to collect suitable samples for subsequent analysis by this method for EC. NIOSH method 5040 requres samples to be collected on quartz filters so that they can be analysed by a technique that involves the staged thermal combusion of the EC to carbon dioxide and following reduction to methane with subsequent analysis by flame ionisation detection (NIOSH 1994). This technique has been used by researchers for some sampling devices as a back–up check or calibration system for the technique involved (Volkwein et al 2008).

On the above basis, the original design of the sample collection system was to collect the raw exhaust straight onto a 47mm quartz filter (SKC Inc. Part No. 225-1830) held within a stainless steel filter holder that was located directly behind the sampling probe. The outlet of the filter holder was connected by several metres of 0.25 inch PFA tubing to a water trap, rotameter type flow meter and vacuum pump.

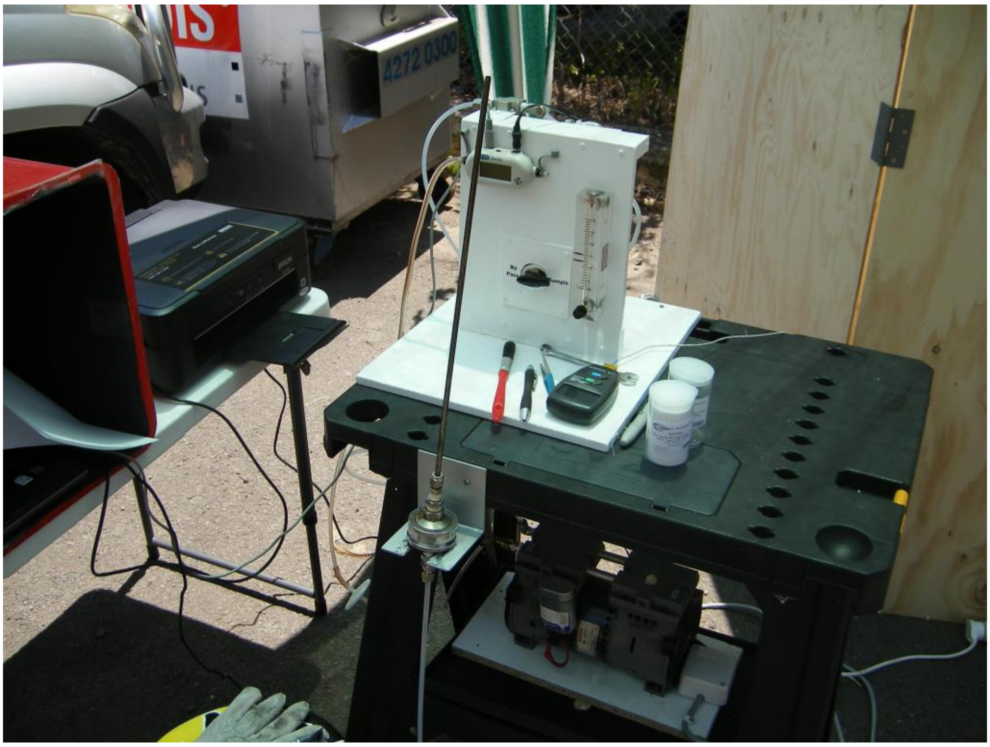
As the flowmeter was located before the vacuum pump and thus under negative pressure, there was a need to calibrate it against a standard system. The density of diesel exhaust was calculated from typical composition data available within the industry and found to be 1.19 kg/m^3 at 20^oC and 101.325 kPa which is very close to that of air (1.2041 kg/m^3) at the same temperature. The flowmeter was subsequently calibrated against a Platon certified rotameter (+/- 1.25% Full Scale Deflection) for a range of airflows from 4.9 $Lmin^{-1}$ to 13.2 $Lmin^{-1}$ On the basis of this calibration the internal flowmeter was adjusted to read the true flow rate of sampled diesel exhaust. Trials of the system indicated that the temperature of the sampled exhaust at the flowmeter under normal conditions was very close to 20^oC due to the loss of heat through the sample line and water trap. This value varied somewhat under high loads but not to a point that the correction of sample volume was deemed necssary. The sampling sytem is illustrated in Figures 4.8, 4.9 & 4.10.

Source: B Davies

Figure 4.8 – Sample probe and filter holder assembly

Source: B Davies

Figure 4.9 – 47mm Quartz filter inside filter holder assembly



Source: B Davies

Figure 4.10 – Complete sampling system

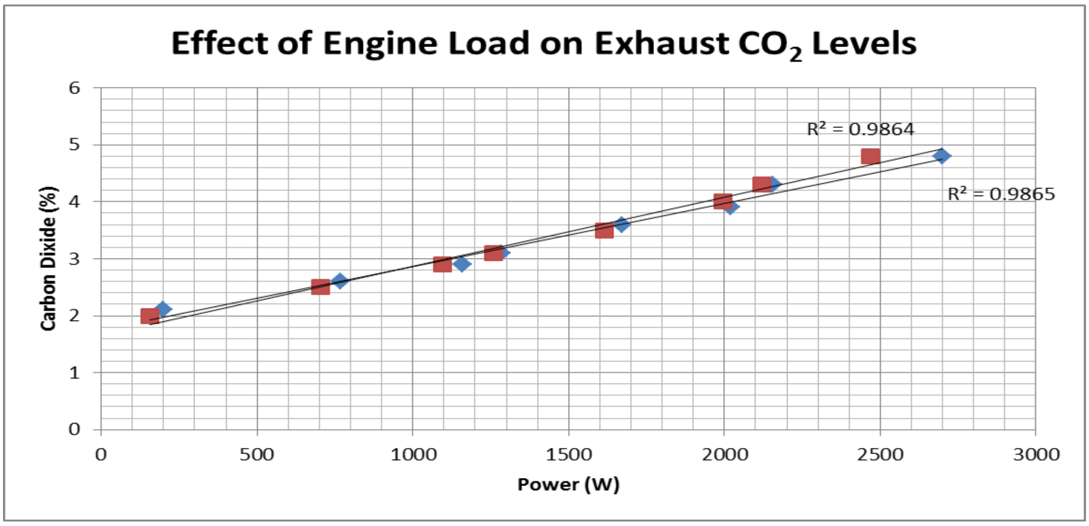
After some initial testing a mass flow meter was purchased to replace the internal flow meter in the sample collection system as it was thought it would be easier to use. This worked for a short time but it eventually failed due to the condensation of moisture from the raw exhaust even though a water trap and protective filter were in line before the unit. As water vapour in the exhaust was always going to be an issue a decision was made in a return to the internal flow meter which was then used for the rest of the project and calibrated at regular intervals.

Following a period of sampling with the 47 mm quartz filters it was realised that the time consuming process of replacing each filter within the holder after each sample would not be practical for any field measurements. A change was made to pre-prepared 37 mm quartz filter cassettes (SKC Part No. 225-401) which had the additional benefit of providing a much clearer sample collection area due to a better seal and reduced cost. The probe assembly was modified to incorporate the new filter cassettes and this design was used for all further testing.

5. INITIAL INVESTIGATIONS USING THE DIESEL PARTICULATE GENERATOR

5.1 Effect of engine load on exhaust carbon dioxide levels

The first investigation undertaken with the DP generator was to see if there was a direct relationship between engine load and CO_2 as it was intended to use CO_2 as an ongoing indicator of engine load. The engine was loaded by connecting two 2000 Watt (W) heaters to the power outlets of the DP generator and by using the low (750 W), medium (1250 W) and high (2000 W) switches on each heater it was possible to achieve varying power demands on the DP generator. From 200 W (only sampling pump running) to 2700 W The levels of CO_2 present at each power level were recorded and the results of duplicate tests are provided in Figure 5.1.



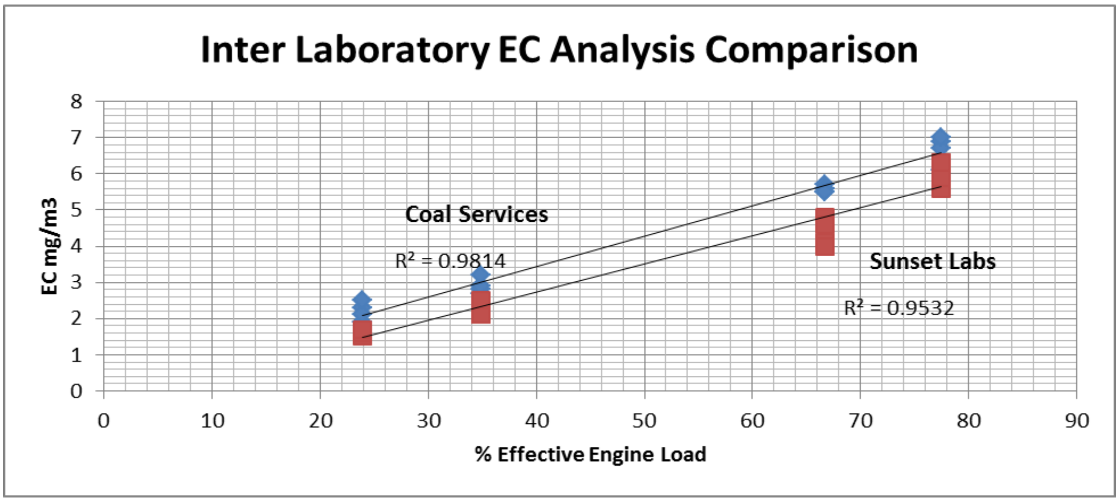
Source: B Davies

Figure 5.1 - Effect of engine load on exhaust CO_2 levels

This outcome was encouraging as it indicated an almost perfect relationship (R^2 values 0.99) and thus the approach could be used to provide different EC concentrations (assuming that EC was related to load) for the calibration of direct reading instruments.

5.2 Inter laboratory comparison of elemental carbon analysis

Prior to the commencement of any instrument comparison trials there was a need to ensure that the results from the laboratory providing the EC analysis (Coal Services) were accurate. With the knowledge of the laboratory concerned, duplicate samples were collected and one set forwarded to Coal Services for analysis and the other to Sunset Laboratories in the USA. Sunset Laboratories is owned by one of the original developers of NIOSH Method 5040 and is reputed to be the best laboratory in the world for this type of analysis. The results of this comparison are detailed in Figure 5.2.



Source: B Davies

Figure 5.2 - Inter laboratory EC analysis comparison

The results of this exercise were excellent and provided a high degree of confidence in the results from Coal Services.

5.3 Distribution of elemental carbon in the exhaust

Following the inter laboratory EC analysis exercise; steps were taken to establish the distribution of EC across the exhaust pipe of the DP generator. This was achieved by attaching two plates to the exhaust pipe (Figure 4.5) so that the 21 cm probe could be inserted into the same spot in the exhaust. The engine was placed under varying loads and the concentration in the exhaust sampled on quartz filters using the collection system indicated in section 4.3. These were then forwarded to Coal Services for analysis. A summary of these results are provided in Table 5.1.

Table 5.1 - Exhaust EC distribution

Exhaust Location	Engine Load (%)	NIOSH 5040 EC mg/m^3
1	16.3	2.2
2	16.3	2.1
3	16.3	2.2
4	16.3	2.2
5	16.3	1.9
6	16.3	1.9
7	16.3	1.9
8	16.3	1.9
1	27.3	2.3
2	27.3	2.3
3	27.3	2.2
4	27.3	2.2
5	27.3	2.3
6	27.3	2.0
7	27.3	2.1
8	27.3	2.1
1	45.7	4.0
2	45.7	3.9
3	45.7	4.3
4	45.7	4.3
5	45.7	4.7
6	45.7	4.5
7	45.7	5.0
8	45.7	4.9

Source: B Davies

This trial was repeated a number of times with similar results, indicating good distribution of EC across the exhaust but some variability at higher loads. This variation was thought to be acceptable given the sampling and analytical errors involved.

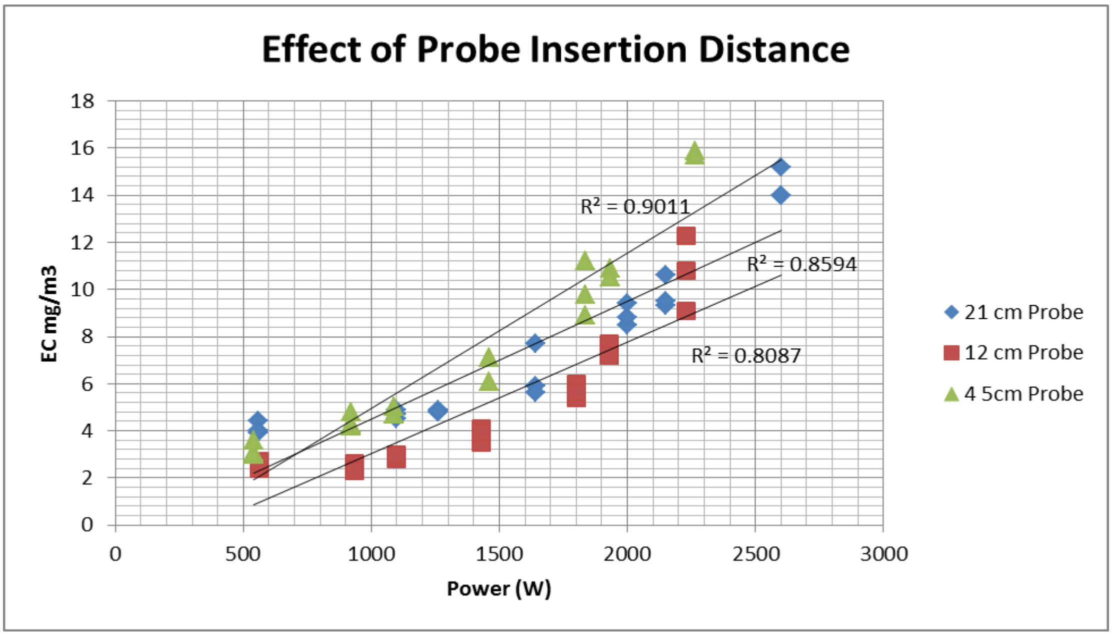
While the EC levels produced by the DP generator are approaching that expected from new generation engines, an attempt was made to increase the fuel to the engine so as to increase the output of EC to a higher level. This proved to be quite a difficult exercise due to the design of the fuel injection system and while EC levels did go up, organic carbon (OC) levels jumped substantially and the exhaust output became offensive to nearby workers due to its smell. Given this the engine was returned to its original state and the selection of any future engine should include an investigation of the fuel management system so to obtain greater flexibility in fuel dosage.

5.4 Effect of sampling probe insertion distance into the raw exhaust

Following discussions with mine site personnel and an inspection of the exhaust outlet of several underground diesel vehicles it became clear that there was a great deal of variation as to how far sampling organisations could insert the probe of a direct reading instrument into the exhaust of vehicles. There were several practical reasons for not being able to consistently sample at the same depth in the exhaust pipe each time and as a result it was decided to undertake a trial on the DP generator to see if there was any difference in EC concentration if the probe was inserted into the exhaust at different depths.

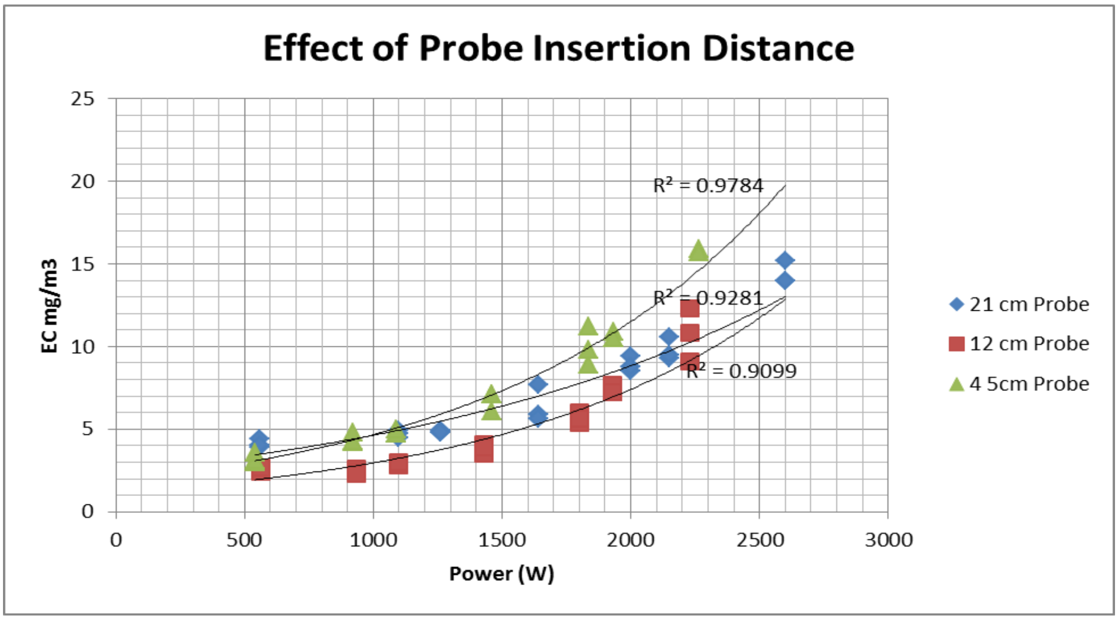
For the trial three separate probes were constructed these being 12, 21 & 45 cm in length. The DP generator was loaded to different levels and each probe inserted to its maximum distance and samples collected at three positions across the exhaust pipe (deemed to be representative of the exhaust profile) and analysed for EC.

The results of this trial are detailed in Figures 5.3 & 5.4 with the former having a linear trend line and the latter an exponential trend line.



Source: B Davies

Figure 5.3 - Effect of probe insertion distance – linear trend line



Source: B Davies

Figure 5.4 - Effect of probe insertion distance – exponential trend line

From the graphs it can be seen that in Figure 5.3 (linear trend line) there is a reasonable relationship for each of the three probes with a significant difference between the 12 and 45 cm probes, however when an exponential trend line (Figure 5.4) is used that relation strengthens and the 45 cm long probe is clearly different to the other two. On this basis it seems that insertion distance plays a role in the analysis of raw exhaust DP and thus there is a need for a standard approach.

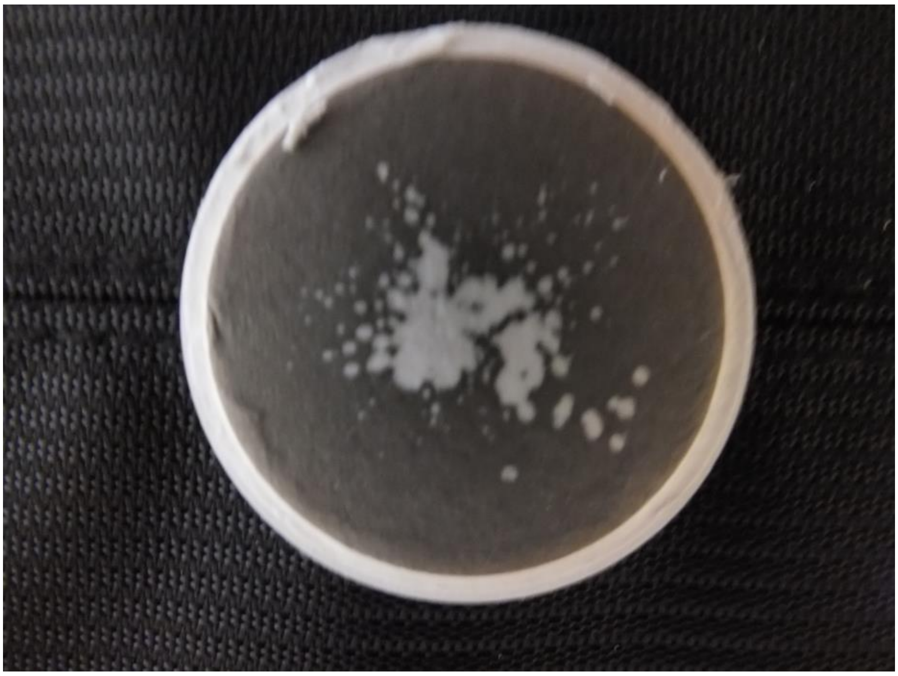
As a result of these findings, it was decided to only use the 21 cm probe for all further investigations as this provided the best compromise with insertion distance and possible exhaust dilution by the general atmosphere.

5.5 Issues with sample collection filters

As discussed in section 4.3 a number of issues arose with the filters used to collect the exhaust samples for EC analysis. These included the delivery of a box of filters that had been contaminated with PVC filters (rather than quartz) however this was not evident to the naked eye and only evident at the time of analysis. Other organisations in Australia using these types of filters were found to be having the same problem which was eventually overcome by the supplier and no further problems arose.

The second issue was the difficulty in obtaining a good seal with 47 mm filters in the stainless steel filter housing due in part to the rubber seal rotating when the housing was closed destroying part of the filter and thus allowing exhaust to by-pass the filter. This was overcome by moving to 37mm pre-packed quartz filters with a backing pad. These filters gave an excellent seal and the problem of filter by-pass was resolved.

The final issue with filters arose when sampling post the water-filled scrubber tank. It quickly became evident that no matter what water trap arrangement was in series with the filter there was significant carry-over and as the exhaust entered the cassette at very high velocity the water quickly dropped out of the exhaust and impinged on the filters making them very difficult to analyse.
An example of the water deposition pattern is shown in Figure 5.5.



Source: B Davies

Figure 5.5 - Water splatter on filter

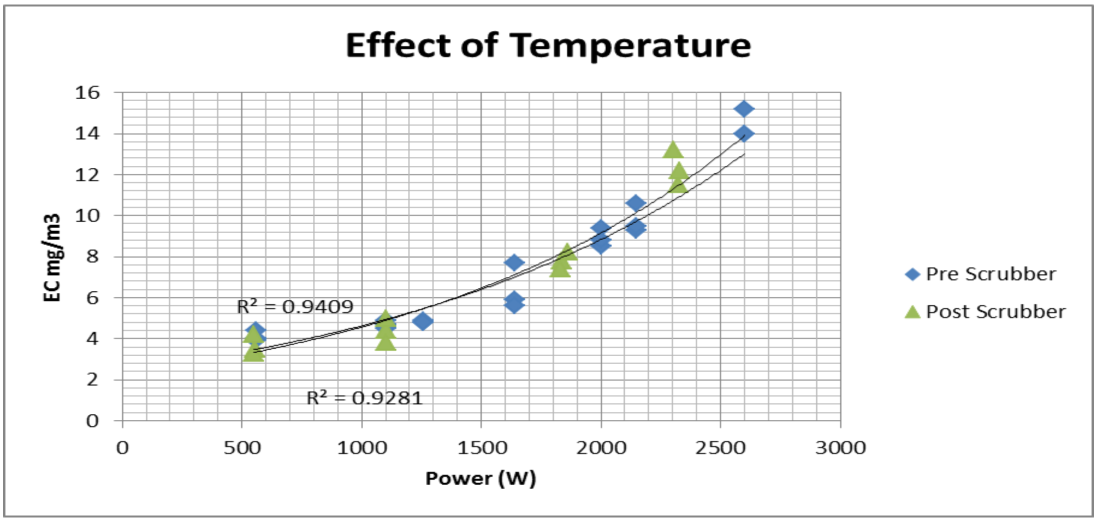
A number of attempts to overcome this problem were tried including the use of different probe types (blocked end with side opening, china man's hat) but without success. It was found however that a more consistent pattern of filter deposition occurred when using a blocked end probe with side openings so all further samples were collected with this style probe.

The result of this investigation is that it is very difficult to use a quartz filter based sampling system if there are very large volumes of water present such as post a water-filled scrubber tank. Much more consistent samples can be obtained when sampling pre any water-based scrubber system which makes the subsequent EC analysis more accurate.

5.6 Effect of temperature on elemental carbon levels in the raw exhaust

Given the findings of section 5.5 that sampling pre the scrubber system was the better option, the potential problem of temperature influence on the sample collection process needed to be considered. A review of the literature indicated that Liu et al (2005) had investigated this problem and found no significant difference in EC levels from exhaust at 25^{o}C and 125^{o}C which is not surprising as EC is non-volatile.

To confirm these findings, samples were collected at varying loads using the DP generator pre and post the water filled scrubber system. The results are described in Figure 5.6 indicate no difference in raw exhaust EC levels pre (approximately 115°C) and post (approximately 45°C) the scrubber system. This indicates that it is possible to sample from the raw exhaust for EC up to at least 115°C or slightly higher based on the work of Liu et al (2005).



Source: B Davies

Figure 5.6 - Effect of temperature on EC

5.7 Summary of outcomes

The outcomes of the initial testing phase of the project can be summarised as follows.

1. The level of CO_2 in the raw exhaust increases with engine load and that provides a means of producing different levels of EC in the exhaust for calibration purposes.

2. The distribution of EC in the exhaust is good but load issues give rise to variations at higher loads.

3. The distance that the probe is inserted into the exhaust appears to have a significant effect on the level of EC measured. This suggests that a standard approach is required to minimise variation in results from different sampling personnel inserting the probe into the exhaust at different depths.

4. Sampling post a water-filled scrubber tank does not appear to be effective due to the large volume of water carry over. Sampling pre the scrubber tank using a blocked end probe with side openings gives a more consistent deposit of material on the sample filter.

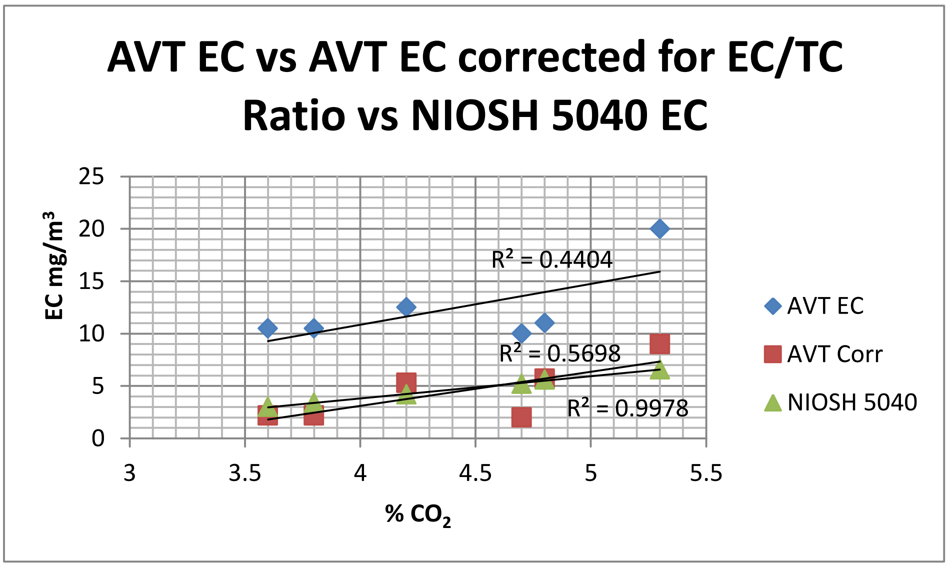
5. There does not appear to be any significant difference when sampling EC at temperatures up to 115°C. This is a significant finding as it means that provided the raw exhaust can be cooled to below 115°C, it should be possible to sample and analyse EC from the gas sampling point on an underground engine in the coal industry rather than the current post scrubber tank approach. If successful this approach should assist in minimising variations in results.

6. COMPARISON OF DIRECT READING INSTRUMENTS VERSUS NIOSH 5040 ELEMENTAL CARBON USING THE DIESEL PARTICULATE GENERATOR

6.1 Preliminary exercise with an AVT 530

The first trial undertaken with a direct reading LLS device using the DP generator was with a new AVT 530 (serial number 0109) on loan from Kenelec Scientific Pty Ltd. This was intended to be a “look and see” exercise but developed into something more substantial.

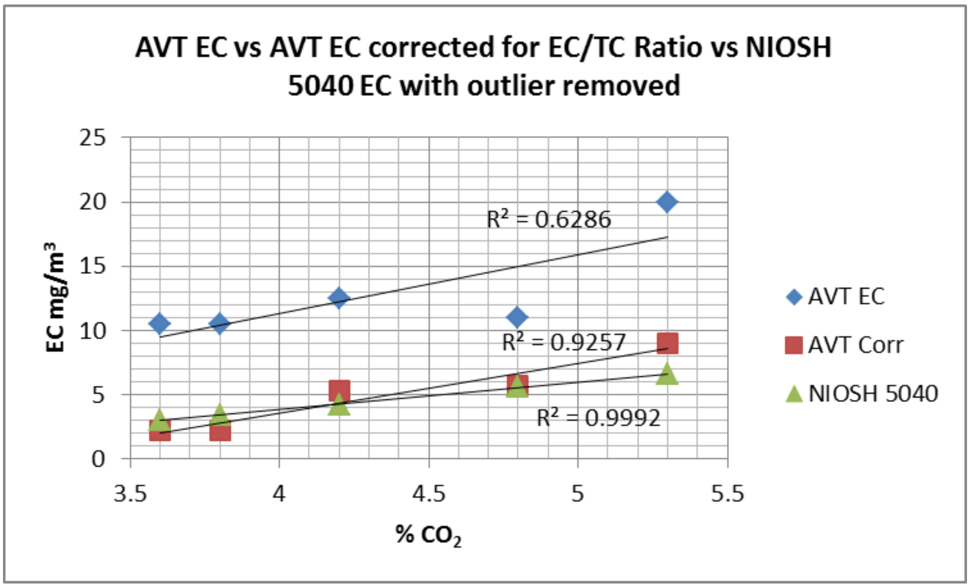
Figures 6.1 & 6.2 provide a graphical representation of the results when comparing AVT 530 EC directly with NIOSH 5040 EC. There does not appear to be any relationship between the AVT EC from the instrument and the NIOSH EC as measured by the filter collection system (Figure 6.1). However when the AVT EC results are converted back to their original total particulate matter (TPM) which is what the instrument actually measures and these values are multiplied by the individual sample elemental to total carbon (EC/TC) ratios, a much better position presents with the AVT R^2 value increasing from 0.44 to 0.57 as against the NIOSH 5040 value of 0.99. The removal of an outlying result from all three graphs increases the AVT EC R^2 value to 0.62 and the corrected AVT EC value to 0.93 (Figure 6.2). This clearly suggests that the factor used in the instrument to convert TPM to EC is not valid for this particular engine.



Source: B Davies

Figure 6.1 - AVT 530 EC versus NIOSH 5040

The EC/TC ratios for the DP generator samples ranged from approximately 0.05 to 0.25, with the lower values being recorded at low load levels when the engine is grossly over fuelled. This was measured by raw exhaust carbon monoxide, which dropped from approximately 650 ppm at low loads to 330 ppm when the engine was working hard at higher loads. The EC/TC ratios were surprisingly consistent over the study suggesting that if an appropriate load level is chosen for routine testing a conversion factor could be established for this particular engine at that particular load.



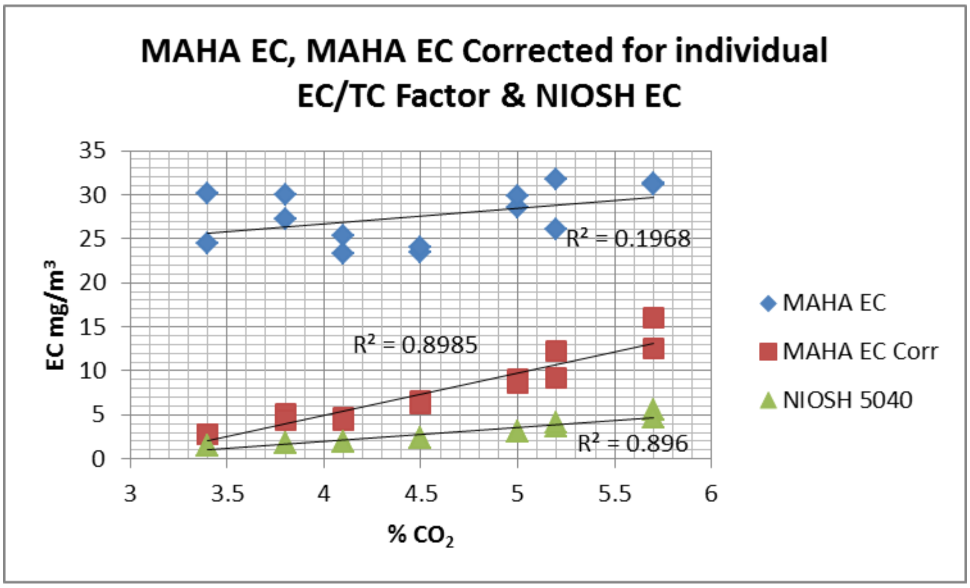
Source: B Davies

Figure 6.2 - AVT 530 EC versus NIOSH 5040 with outlier removed

6.2 Preliminary exercise with a MAHA MPM – 4M

A similar exercise was conducted using a MAHA MPM – 4M (serial number 537165-004) owned by Coal Mines Technical Services with a similar outcome. As before the EC results provided by the manufacturer were used to convert the values back to TPM and these were then multiplied by the individual EC/TC ratios for each sample collected by the NIOSH 5040 method.

The results of this exercise are provided in Figure 6.3.



Source: B Davies

Figure 6.3 - MAHA EC versus NIOSH 5040

Again the direct correlation of MAHA EC versus NIOSH 5040 shows no relationship; however this dramatically changes when the individual sample EC/TC ratios are used as the conversion factor. This is further evidence that the factor used by the manufacturer to convert TPM to EC is not appropriate for this particular engine.

6.3 Appropriateness of current instrument conversion factors

The results detailed in sections 6.1 & 6.2 cast doubt on the current practice within the industry of applying one conversion factor to cover all engine types when using direct reading instrumentation. This factor is different for the AVT 530 and the MAHA MPM – 4M (0.52 and 0.46 respectively). Reference to the NSW Department of Primary Industry report (NSW 2004) confirms that a factor of approximately 0.5 was found to be appropriate for Caterpillar 3304 & 3306, KIA & Perkins engines that were predominant within the industry at that time. The results for caterpillar 3126 engines, which were just becoming available within the industry, did not show the same relationship albeit the number of engines available for sampling was few at that time.

It is also interesting to note that dynamometer tests for the Caterpillar 3126 were not consistent to other engines when looking at TPM, which is supported by Vouitsis, Ntziachristos & Samara (2003) who found a similar effect with TPM suggesting that the use of TPM for raw exhaust DP estimation should also include reference to engine type. More work is required to establish if the LLS TPM to TPM (mass) correlation changes with engine type before this metric can be universally applied to engines in mine diesel fleets.

The conclusion of the NSW Department of Primary Industry report (NSW 2004) was in part that the type of engine must be taken into account when assessing the results from new generation engines (Caterpillar 3126 at that time) when using LLS measurement techniques.

Given the previous work (NSW 2004) and the findings detailed from the current study there is a need for the coal industry to establish the EC/TC ratios for those new generation engines entering underground diesel fleets. These factors could then be incorporated into the LLS devices with hopefully a much better outcome in terms of determining raw exhaust EC levels. If the industry does not wish to undertake such a task it would be possible to revert to TPM as the measurement technique but there would still be a need to confirm or dismiss the findings of the Department of Primary Industry report (NSW 2004)and Vouitsis, Ntziachristos & Samara (2003) in respect to TPM and engines such as the Caterpillar 3126.

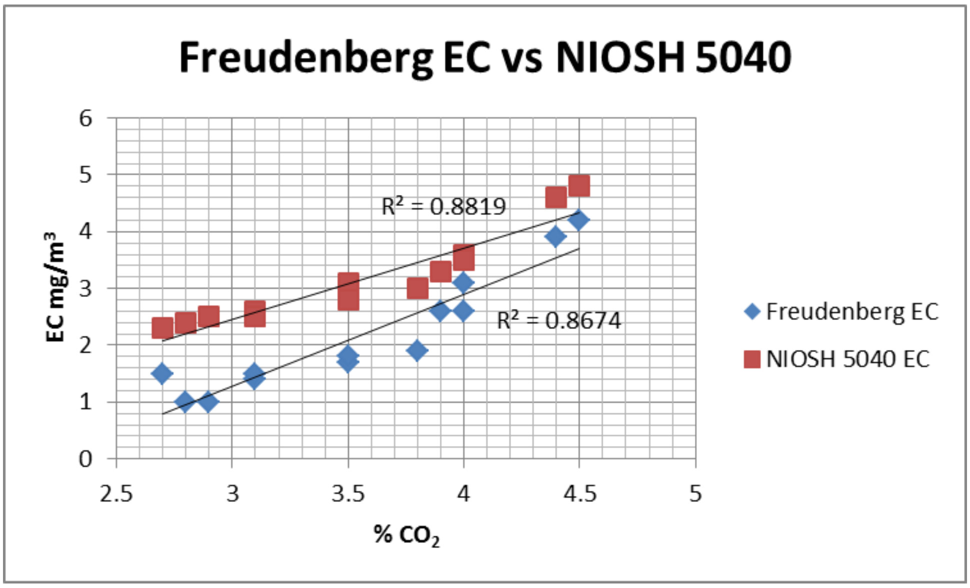
6.4 Freudenberg sampling system

During the course of the project a prototype system to collect DP samples from the raw exhaust for subsequent EC analysis became available from Freudenberg Filtration Technologies (Aust) Pty Ltd. This device has its origins in the NIOSH project (section 3.2) and was further refined by personnel at a local mining company some years later. The proof of concept unit was constructed of parts from the defunct Tower Colliery R & P 5100 system however it was cumbersome and impractical for field use.

The device (Figure 6.4) is designed to fit in a carry case and only collects samples for subsequent analysis by a laboratory. Given the potential of this system to collect EC samples from any diesel engine in the field and to check the calibration of LLS instrumentation a trial was conducted to see how the device performed against the NIOSH 5040 method used in the current project. Figure 6.5 shows that there was a very good relationship between the two devices and subject to some modifications to make the system more robust for field use could be a valuable calibration or assessment tool (if instant results are not required).

Source: Freudenberg Filtration Technologies

Figure 6.4 - Freudenberg sample collection system

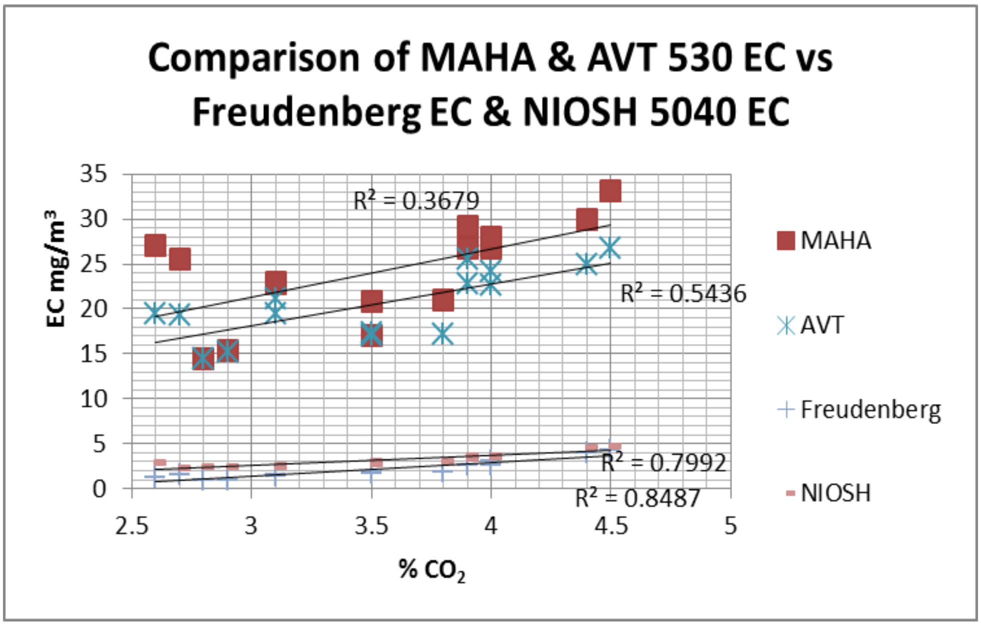


Source: B Davies

Figure 6.5 - Freudenberg EC versus NIOSH 5040 EC

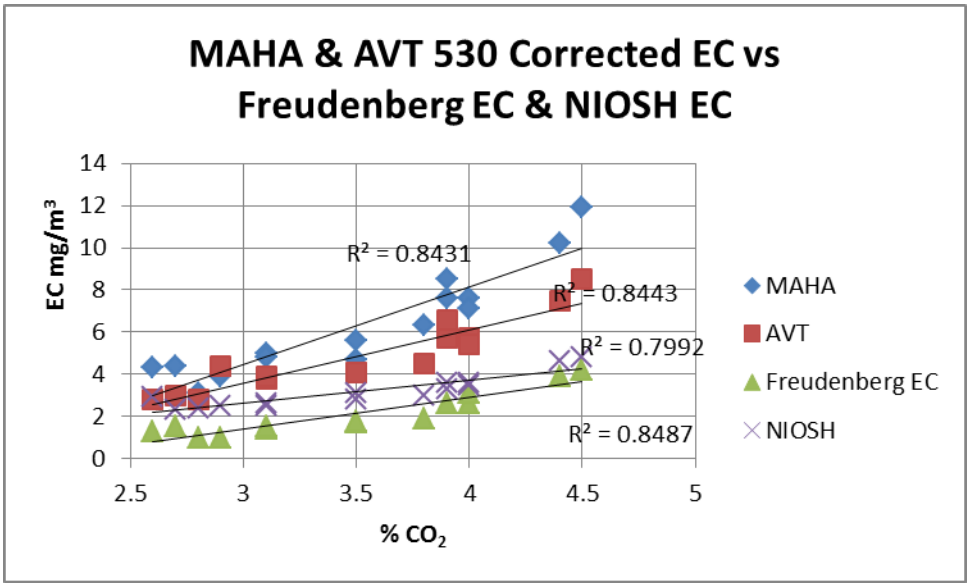
6.5 Comparative exercise involving all available instrumentation

The last trial conducted with the DP generator was a comparison of the AVT 530, MAHA MPM – 4M, Freudenberg device against the NIOSH 5040 method over varying load levels. Sampling was timed so all samples were collected at the same time. Given the preliminary findings (sections 6.1 & 6.2) all AVT 530 & MAHA MPM – 4M results were corrected for the EC/TC ratios derived from the NIOSH 5040 samples. The results of this trial are detailed in Figures 6.6 & 6.7.



Source: B Davies

Figure 6.6 - Instruments EC versus NIOSH 5040 EC



Source: B Davies

Figure 6.7 - Instruments corrected EC versus NIOSH EC

In this instance a similar picture presents with the EC reported directly from the two direct reading instruments having no correlation (R^2 0.37 and 0.54) but significant improvement when the individual sample EC/TC ratios are used (R^2 0.84 and 0.84). The correlation between Freudenberg EC (measured as NIOSH 5040 EC) and NIOSH 5040 EC, measured by the system in section 4.3, showed very good agreement.

These results again support the view that the EC/TC ratio must be known for engines different to those evaluated previously (Caterpillar 3304 & 3306, KIA and Perkins) if an accurate assessment of EC is to be made for the engine used in this exercise.

6.6 Summary of outcomes

The outcomes of the direct reading instrument comparison phase of the project can be summarised as follows.

1. The use of generic factors in direct reading instruments to convert TPM to EC is not valid if the engine under assessment has a significantly different EC/TC ratio than those engines upon which the factor was established.

2. If the correct EC/TC factor is known for a particular engine (at a particular load), direct reading instrumentation such as LLS devices are a useful tool in providing quick raw exhaust EC results.

3. If the coal industry does not wish to determine EC/TC ratios for each engine type then the use of TPM as a measurement metric is a possibility but the concerns raised in the NSW Department of Primary Industries

report (2005) and Vouitsis, Ntziachristos & Samara (2003) would need to be investigated to ensure that the LLS TPM and mass TPM (standard method) correlation are consistent for all engine types.

4. The Freudenberg sample collection system appears to be a useful tool for the collection of raw exhaust DP samples for subsequent EC analysis and can be used as an audit check on instant reading devices such as LLS instrumentation.

7. DEVELOPMENT OF A PROTOCOL FOR SAMPLING FROM THE RAW EXHAUST GAS SAMPLING POINTPOINT

7.1 Reasons for change

As discussed in section 5.5, the use of quartz filters does not lend itself to the collection of DP from the raw exhaust post a water-filled scrubber tank.

Following this finding, discussions were held with personnel familiar with monitoring engines for DP (Hart 2013, Anyon 2013) and also a mine engineer (Clinton 2013) and all agreed that monitoring the raw exhaust of a diesel engine fitted with a water-filled scrubber tank, and in many cases a disposable exhaust filter, was not the best option. In all cases those consulted agreed that sampling from the statutory gas sampling point if possible would provide a much better and consistent source of DP for analysis. The fact that all engine systems fitted with a scrubber tank have a permanent exhaust back-pressure ensures that a reasonable gas flow should exit the gas sampling point, provided the fitting is well maintained and clear of obstruction.

Some reasons for this change include:

1. The design of exhaust systems especially on engines fitted with disposable filters are such that the exhaust commonly exits the filter housing through multiple ports many of which are difficult to access.

2. Some systems are such that if they do not have an exhaust outlet that is straight and the probe must be inserted so that a bend in the exhaust pipe is negotiated with resultant probe alignment difficulties.

3. There is a need to standardise the sampling procedure for DP in the raw exhaust of engines and sampling from the gas point provides a much better option to achieve this outcome. This will help minimise variations in raw exhaust results.

4. The water-filled scrubber tank of many engine systems when under load blows a considerable amount of water through the exhaust pipe thus making sampling difficult. A move to sampling from the gas point would alleviate this difficulty and while the exhaust would still have water vapour present (NSW 2004), it would be at much lower levels than post a scrubber tank.

5. Sampling from the gas point would give a much better picture of the engine status as only pure exhaust would be sampled.

6. The use of sampling onto quartz filters as described in this report would become a viable reference method for the measurement of DP in the raw exhaust of diesel engines.

One factor that has always restricted the use of the gas point is that the exhaust is at a much higher temperature than post the scrubber tank and as historical methods of sampling and analysis have required the sampling temperature to be below approximately 50^oC, this option has not been considered viable.

The work of Liu et al (2005) and the findings of the current research (section 5.6) indicate that EC can be reasonably sampled up to a temperature of 125^oC. In addition, if the exhaust could be cooled then this opens up this position being useful for sampling by other monitoring methods.

In summary, sampling from the gas sampling point offers considerable benefits for the monitoring of raw exhaust DP and while this aspect is outside the aims of this project some simple investigations were undertaken to see if was possible to collect a sample of raw exhaust for subsequent EC analysis.

7.2 Prototype sampling system

Following the discussions with individuals listed in section 7.1, the author discussed the possibility of monitoring from the gas point with personnel from ERP Engineering Pty Ltd (ERP). As the result of that discussion, ERP independent to this project developed a sampling system (Figure 7.1) and offered it to the author for evaluation.

The basis of the system is that raw exhaust is forced through a connection pipe by the exhaust back-pressure into a cooling coil before entering a plenum where it is mixed. A pressure gauge and ball valve are fitted to the plenum so that the back-pressure can be managed and samples are collected marginally above zero back-pressure. The ball valve also acts as a drain for any water vapour condensed from the exhaust.

To ensure that samples are collected in the same location the sample collection opening is designed such that any inserted probe cannot touch the sides of the plenum.

Several prototypes were evaluated (section 7.3) and the outcomes used to develop a working system (Figure 7.1).

Source: B Davies

Figure 7.1 - Prototype gas point sampling system

7.3 Trials at Mine-Pro (NSW) Pty Ltd

Several basic trials of the prototype DP gas point sampling system were conducted at Mine-Pro (NSW) Pty Ltd, Unanderra NSW. Mine-Pro is a certified maintenance organisation and they provided access to several mine vehicles that were undergoing maintenance so that the system could be tested.

The first test undertaken was to measure the temperature of the exhaust from a Caterpillar 3306 engine inside the plenum under idle and load conditions. The temperature was measured at 36^{o}C at idle and 56^{o}C at load which was a significant reduction from the gas temperature at the manifold which was in excess of 200^{o}C (off scale of meter).

Several samples were then collected at idle and load using the LLS device and the quartz filter method. The results for this basic exercise are listed in Table 7.1.

Table 7.1 - Initial test of prototype sample cooling device on a Caterpillar 3306 engine

Engine Status	LLS Device No. 1 EC mg/m^3	NIOSH 5040 EC mg/m^3	EC/TC Ratio
Idle	2.3	5.4	0.55
Load	6.8	11.8	0.67

Modifications were made to the prototype device by ERP so as to make attachment to the engine gas outlet easier and further testing was undertaken this time on a Caterpillar 3126 engine the results of which are listed in Table 7.2.

Table 7.2 - Testing after modifications on a Caterpillar 3126 engine

Engine Status	% CO_2	LLS Device No.1 EC mg/m^3	LLS Device No.2 EC mg/m^3	NIOSH 5040 EC mg/m^3	EC/TC Ratio
Idle	4.1	25	8	13	0.53
Constant Load	8.9	97	65	48	0.83
Flight Revs	6.5	55	26	35	0.65

These results showed much more variability but this is very likely to have resulted from the inability to reproduce the engine load conditions as all tests were conducted separately over one minute with a cooling period in between. Consequently direct comparisons are invalid but the general scope of the results gives encouragement that sampling from the gas point using a suitable cooling and mixing system is possible.

It is interesting to note the EC/TC ratio for the Caterpillar 3126 engine under load as 0.83 (Table 7.2) while that of the Caterpillar 3306 engine being 0.67 (Table 7.1). Neither of these equates exactly to the factors used in the LLS instruments and while this is anecdotal evidence at best it does support the views expressed in section 6.3 on the appropriateness of current conversion factors.

7.4 Summary of outcomes

The brief investigation of sampling at the gas point rather than the currently used location of post the scrubber tank, has shown that the extraction of a sample of raw exhaust at a reasonably low temperature is possible and that raw exhaust DP measurements can be undertaken.

This aspect was not included in the goals of the current research but developed as a result of findings associated with the collection of DP on filters. This process needs to be more thoroughly researched by personnel who have routine access to mine vehicles so that a more comprehensive picture of the viability of this approach can be obtained. The Freudenberg EC sampling system and a LLS instrument would complement one another for this task as not only could the mixing and cooling system be evaluated but the EC/TC ratios for various engine types could be obtained (section 6.3), thus potentially providing more accurate results to be obtained for EC when monitoring by LLS instrumentation.

8. SUMMARY OF CONCLUSIONS

As the result of the research conducted in this project the following conclusions can be made:

1. It is possible to use a small diesel generator to produce an exhaust stream that provides varying levels of EC at different engine loads with a reasonably even distribution across the exhaust pipe. This then provides a valuable means for the calibration of instrumentation directly to NIOSH method 5040 which is an internationally recognised standard for health assessment.

2. The use of laser light scattering (LLS) instruments with generic factors to convert the measured total particulate matter (TPM) to EC is only valid for the types of engines that they were originally derived. On this basis every new type of engine that enters underground diesel fleets in coal mines should be evaluated to establish if the current factor remains appropriate. If this occurs, direct reading instrumentation (e.g. LLS) should provide a useful means for the quick measurement of raw exhaust EC. If the industry does not wish to undertake this work then TPM may be a possible metric for the estimation of raw exhaust DP however clarification of the variation in correlation issues raised by Vouitsis, Ntziachristos & Samara (2003) and the NSW Department of Primary Industries report (NSW 2004) will be required before this alternate metric could be used on all engines in current diesel fleets. In either case, checks at appropriate intervals by other potentially slower means would add significantly to the confidence of results obtained by LLS.

3. The sampling of raw exhaust DP using quartz filters for subsequent EC analysis is a viable alternative to current technologies, however the process does not lend itself to sampling post a water-filled scrubber tank or for the provision of instant results. It does however provide an excellent means of providing a check method for direct reading instrumentation.

4. The Freudenberg sampling system appears to be suitable for the collection of raw exhaust for subsequent EC analysis as a check method for LLS devices provided a number of modifications to the tested prototype recommended to the manufacturer are implemented

5. The depth that a probe is inserted into the raw exhaust of an engine appears to have an effect on the concentration of EC measured. This may be a factor in the high level of variability of results experienced by mines when using different testing organisations. For the engine used in this project a probe of 21 cm appears appropriate.

6. No effect on raw exhaust EC concentration caused by temperature was observed when sampling the raw exhaust at approximately 115^{o}C compared to that at 45^{o}C. This is a significant finding as it allows the gas sampling port on the manifold of underground diesel engines used in the

coal industry to be the place of choice to collect samples. This should have a major effect on minimising sampling errors provided the exhaust is appropriately cooled and mixed.

7. The device developed by Emission Reduction Products Engineering Pty Ltd to collect a suitable sample from the gas sampling point appears to work but further evaluation is required over a range of in service vehicles.

9. RECOMMENDATIONS

Arising from the above outcomes the following recommendations are put forward for consideration by the coal industry.

1. If LLS devices are to be used for the measurement of raw exhaust EC the coal industry needs to establish the elemental carbon to total carbon (EC/TC) ratios for new generation engines so that more accurate results for raw exhaust monitoring of these types of engines can be obtained when using direct reading instrumentation. To do this a detailed study of a range of equipment needs to be undertaken which could be progressed in concert with the evaluation of monitoring from the gas sampling point, rather that the currently used exhaust pipe. Longer term all new engines should have their EC/TC ratio established at the certification stage in a manner consistent with how the engine will be tested when in-service.

   If TPM is chosen as the preferred measured metric, LLS TPM versus standard method TPM correlations (mass and size fraction) for all newer design engines in service (i.e. introduced post 2002) should be determined. Longer term this could be established at the certification stage in a manner consistent with how the engine will be tested when in-service.

2. Irrespective of the metric used a standard method for the sampling of raw exhaust for DP needs to be implemented by the industry. The current monitoring approach does not detail probe insertion distance, probe type or any requirements for the calibration of measurement instrumentation to an internationally accepted standard. Any such standard method should be developed with the input of all stakeholders so that one single approach is adopted by all in the industry.

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11. ACKNOWLEDGEMENTS

During the course of the project considerable assistance has been received from the following persons or organisations and their valuable contribution is gratefully acknowledged. I sincerely apologise in advance to anyone who may have contributed to the project and is not listed below.

Paul Bartley, Brian Horton & Michael Koh - ERP Engineering Pty Ltd
Steve Brown – Consultant to Kenelec Scientific Pty Ltd
Penny Cross – University of Wollongong
Steve Gledhill – Freudenberg Filtration Technologies Pty Ltd
Peter Hart & Peter Mason – Coal Mines Technical Services
Jen Hines – BHP Billiton Pty Ltd
Gary Mace – Coal Services Pty Ltd
Paul Montague & Peter Langley – Kenelec Scientific Pty Ltd
Peter Roope – University of Wollongong
Peter Williams – Mine–Pro (NSW) Pty Ltd
Julie Woods – University of Wollongong

Finally, it is appropriate to acknowledge the substantial contribution of the Coal Services Health & Safety Trust for funding this project. The assistance of Bruce Grimshaw, the Trust Secretary and Lynne Magee the project monitor is gratefully acknowledged.

12. APPENDIX

Computer aided diagram of exhaust mixing system