Managing Diesel Particle Emissions through Engine Maintenance - an Australian Perspective

Peter Anyon
Managing Director, MicroCAD Australia Pty Ltd, Ninderry, Queensland, Australia.

ABSTRACT: Exposure to the microscopic particles in diesel engine exhaust can lead to serious health problems, including the incidence of cancers, heart disease and increased susceptibility to respiratory ailments such as pneumonia, bronchitis, and asthma.

In Australia, mining companies and state government authorities are actively responding to this major occupational health and safety issue. Their initiatives place considerable emphasis on routine monitoring of diesel particle matter (DPM) exhaust emissions, both for engine benchmarking and as a part of routine engine maintenance. Implementation strategies follow two complementary paths:

- determination of individual engines' emission signatures, combined with periodic engine re-certification; and
- co-operatively agreed industry-government engine maintenance programs, which are subject to audit.

Both strategies place heavy reliance on real-time measurement of DPM concentrations in engine exhaust, using ruggedized instrumentation, mainly based on laser light scattering photometry.

Adding value to this cooperative approach, industry has also collectively funded a government agency to design and manage a database, into which the results of all routine DPM testing can be uploaded directly by individual mines. This win-win outcome is a great example of how cooperative action between governments and industry can deliver the goods: in this case a safer working environment, more efficient energy use and the capacity to benchmark performance with industry peers

1 Introduction

Medical research has clearly shown that human exposure to fine particles in diesel exhaust can lead to serious health problems, including the incidence of cancers, heart disease and increased susceptibility to respiratory ailments such as pneumonia, bronchitis, and asthma..

Although health costs specific to the mining industry are not readily available, broader-based studies on the economic and social impacts of airborne particles paint an alarming picture.

A 2006 World Health Organization report concluded that, in the European Union, health costs arising from human exposure to fine particles in diesel exhaust amounted to around US$80billion per annum. Moreover, the WHO also estimated that this pollution currently shortens the life expectancy of every resident of the EU by an average of almost nine months.

In the confined working environment of underground mines, diesel particulate matter (DPM) reduction is an extremely important issue and a great deal of effort is being expended to minimize the potential for this dangerous airborne pollutant to affect the wellbeing of workers at the coal face.

Regulators, the mining industry, and their equipment suppliers have worked together to develop and validate a range of innovative, practical measures for reducing DPM levels.

This paper provides an overview of some of the strategies currently being implemented in Australia.

2 Why are Diesel Particles a Hazard?

2.1 Particle Composition

The most significant DPM constituents are carbon soot particles. together with a range of organic aerosols, some of which are highly toxic and suspected or known carcinogens. The US Clean Air Act defines the most significant of these to be benzene, 1,3-butadiene, acetaldehyde and formaldehyde.

As well as being highly reactive in their own right, soot particles can also adsorb these "air toxic" compounds on to their surface through mixing and agglomeration in the exhaust stream. Safe concentration levels for air toxics have not yet been determined, and some researchers believe there may be no lower safe limit.

Elemental carbon (EC) particles, which are the regulated component of diesel particles in both the USA and Australia, typically represent over 50% (by mass) of total DPM. Recent Australian research *(New South Wales Department of Primary Industries, Mine Safety Technical Services, 2004)*, based on mechanically controlled engines using 50ppm sulfur fuel, measured the average EC component to be around 65% of total DPM mass.

2.2 Particle Size

The particle sizes deemed most dangerous to human health are commonly defined as those with a nominal diameter less than 10 microns (PM_{10}) or, more recently, less than 2.5 microns ($PM_{2.5}$). In practice well over 90% of all DPM is less than one micron with the greatest mass concentration typically around 0.3microns (0.0003mm) diameter. The greatest numerical concentration consists of particles more than an order of magnitude smaller. Figure 1 puts a visual perspective on the relative size of 0.3 micron particles, compared with a human hair.

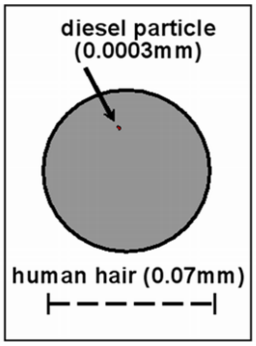
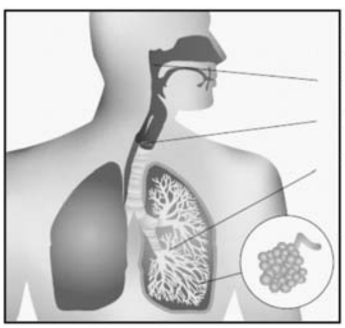


Figure 1. A typical diesel exhaust particle is more than 200 times smaller than the diameter of a human hair.

Sub-micron and nano-range particles can readily by-pass the body's defense mechanisms and penetrate to the deepest and most sensitive areas of the lung, carrying with them their load of toxic compounds. Figure 2 illustrates the zones in the respiratory system which can be reached by progressively smaller particles.



Penetration Zone	Particle size
Nose and throat	5 – 10 micron
Windpipe	3 – 5 micron
Bronchia	1 – 3 micron
Alveoli	0.05 – 1.0 micron

Figure 2. Smallest particles penetrate deeper into the most sensitive areas of the lung.

This illustration shows clearly why diesel particles, almost all of which are in the size category that can do most damage to human health, are the focus of intense activity.

3 DPM Reduction Strategies

By way of background, this sub-section briefly discusses the "menu" of practical options for reducing DPM concentrations in underground mines. These options are by no means specific to Australia, as the same DPM exposure issues are being faced in all mines.

In essence, the fundamental approaches can be distilled down to just two basic strategies: increase ventilation flow and/or reduce the amount of DPM being generated.

Although the control of ventilation air is certainly a very important element in the strategy mix, upgrading ventilation systems to deliver significantly increased flows would most likely involve very large capital and ongoing operating costs. In some cases it may not even be a practical option. So, while effective ventilation control is vitally important, it is unlikely to be a complete solution for meeting DPM exposure reduction targets.

Approaching the solution from the opposite direction, ie, by reducing the amount of DPM generated, four mainstream paths may be followed:

- use cleaner (low sulfur or non-fossil) fuels;
- upgrade to newer technology, cleaner engines;
- incorporate exhaust after-treatment devices (filters, catalysts, etc);
- implement targeted, emission-related maintenance.

Where appropriate and commercially justified, combinations of the above strategies may be implemented as their effects are essentially cumulative.

Switching from high (>500ppm) to low (<50ppm) sulfur diesel can reduce particle emissions by 10% or more from engines in good mechanical condition, regardless of their technology level.

Although only very small further DPM reduction benefits flow from the use of 10~20ppm sulfur fuel, there can be major indirect benefits through technology enabling.

Many exhaust after-treatment systems, most notably regenerating diesel particle filters (DPFs) and diesel oxidation catalysts (DOCs), demand fuels with less than 20% sulfur content for most effective operation and long-term durability..

In Australia since 2006 the sulfur content of all diesel fuel must not exceed 50ppm, reducing to 10ppm in 2009.

Bio-fuels are processed from a number of vegetable or animal-based sources. As a consequence, the feedstock and quality of processing can strongly influence their emission characteristics. Overall, published test data indicate that biodiesel can deliver particle emission reductions in the order of 20% compared with traditional pump diesel, but the penalty can sometimes be a small increase in oxides of nitrogen (NOx) – typically around 5%. Sulfate emissions are effectively zero.

Although not yet widely adopted, a number of Australian mining companies are actively researching the potential for using biodiesel in their underground operations.

Over recent years, technology has dramatically improved the intrinsic performance and environmental credentials of on-road diesel engines.

Ultra-high pressure common rail fuel systems, coupled with advanced injector technology capable of delivering up to nine separate injections per power stroke, have transformed the power and emissions performance of these engines.

Regenerating diesel particle filters can remove up to 99% of DPM from the exhaust stream, with claimed durability exceeding 200,000miles (4,000 hours) of operation. Urea or ammonia based selective catalytic reaction exhaust after-treatments, which are now being introduced to meet stringent new certification standards, are claimed to cut NOx emissions by up to 90%.

To the extent that mine safety regulations and commercial prudence permit, many of these technologies will be migrated into mining engine packages, delivering very significant reductions in DPM and gaseous emissions.

But in the short to medium term, the maximum benefits will flow from improved, targeted engine maintenance. Emissions from existing in-use engines remain a problem, as a badly maintained diesel engine can have PM emissions many times higher than an equivalent, well-maintained example. Fortunately, good maintenance can, in most cases, drastically reduce emissions from the high polluters.

Although there is not yet a great deal of data for underground mining engines, the trends are starting to look very similar to the on-road vehicle experience, with a relatively small number of badly maintained engines accounting for a disproportionately large amount of total pollution (see Figure 3). These engines are also the ones that offer the greatest emission reductions.

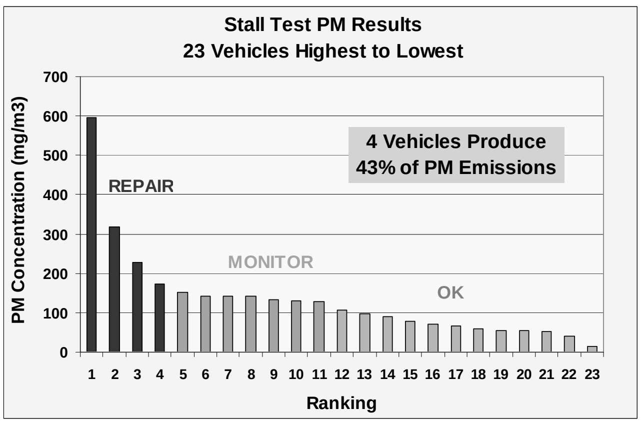


Figure 3. Small Number of Vehicles Generate Large Share of DPM Emissions.

Maintenance-related emission reductions, including some case studies, are discussed in Section 8.

4 Australian DPM Regulation

Although individual Australian states have responsibility for setting DPM exposure limits in underground mines, there is a broad understanding between jurisdictions to achieve consistency in outcomes wherever possible.

This understanding has matured through the National Mine Safety Framework, which is an initiative of the Ministerial Council on Mineral and Petroleum Resources and was initially developed by the Chief Inspectors of Mines. The seven strategies of the Framework are:

- a consistent nationwide legislative framework;
- competency support;
- compliance support;
- a consistently applied enforcement protocol;
- effective data collection, management and analysis;
- consistent approaches to consultation; and
- a strategic approach to mine safety and health research and development.

In 2005, the Ministerial Council established a tripartite Steering Group, with representatives from the workforce, industry and State, Territory and Australian Governments to guide the development and implementation of the Framework.

In respect or DPM, Australia has a mixture of regulation, guidelines and voluntary agreements, with a common target of achieving a maximum respirable DPM level of 0.1mg/m^3 elemental carbon (EC).

This closely parallels the May 2008 MSHA limit of 0.16mg/m^3 total carbon (equivalent to 0.12 mg/m^3 EC).

The Australian DPM reduction story also contains a model example of government - industry cooperation, the benefits of which are directly flowing through to the health and safety of mining personnel.

Around three years ago the Queensland Department of Mines and Energy brought together representatives of the underground coal mining and allied industries to discuss and develop strategies for reducing worker exposure to DPM.

Rather than issuing prescriptive regulations, the Government invited mine managers to, jointly with the Government, formulate strategies to achieve the desired outcomes. This was proposed on the basis that mines would be subject to audit, with the prospect of government intervention if air quality targets were not achieved. Industry responded very positively, and over a 12 month period agreement was reached on common approaches, test methods and test reporting procedures.

Adding value to this cooperative approach, industry also collectively funded the mines safety testing and research agency SIMTARS to design and manage a database, into which the results of all routine DPM testing can be uploaded directly by individual mines.

This growing database serves both as a repository where mines can store their test records and collectively set benchmarks for the performance of engine types used in the mining industry.

This win-win outcome is a great example of how cooperative action between governments and industry can deliver the goods: in this case a safer workplace environment, more efficient energy use in the workplace and the capacity to measure and compare performance with industry peers.

New South Wales has also recently issued its guidelines for DPM management (MDG 29 – Guidelines for the Management of Diesel Engine Pollutants in Underground Environments), which recommends test methods and exposure limits consistent with those used in Queensland.

5 Test Development and Instrument Evaluation

Selection of the DPM test procedures and measuring equipment for use in Australia was based on a comprehensive test and evaluation program completed over the period 2002-04 *(New South Wales Department of Primary Industries, Mine Safety Technical Services, 2004).*

The project comprised two major phases: a series of laboratory tests to evaluate and correlate different instruments under controlled conditions, followed by field testing at five coal mine sites.

Several measuring technologies and instruments were evaluated, including three laser light-scattering instruments and a NIOSH pressure-drop method. For reference, the testing also included a Bosch smoke meter and an R&P Elemental Carbon Analyser, both of which have been used extensively in mines over recent years.

Each instrument was first cross-correlated with the standard dilution tunnel method (using weighed filter papers) and other recognised methods. Tests were conducted using three engines operating on an engine dynamometer under tight control, using a single fuel. The tests involved steady-state conditions, and also steady state with accelerations.

For field testing a simple test procedure (see Section 6) has now been formalized and recognized by the Queensland and New South Wales government agencies, and is likely to be adopted nationally.

Both the light-scattering technology and the NIOSH pressure drop method were found to give acceptable measurements of DPM concentration, although some enhancements were recommended to improve their usability in routine mining operations.

From this comprehensive groundwork, commercially available instruments have been produced and mines around Australia are progressively introducing monitoring of engine exhaust DPM levels as a standard workshop procedure to enhance the effectiveness of their engine maintenance.

6 Australian Test Protocol

For DPM testing to be widely adopted (and reliably performed) it must be easy to follow, require minimal training and leave few opportunities for error. This applies to both the test equipment and the test procedure.

Most diesel powered equipment operated underground employs a torque converter to transfer engine power to the remainder of the powertrain. This supports the use of a two-mode test cycle based on the engine either idling with the transmission engaged, or under power with the accelerator pedal fully depressed.

The test procedure adopted in Australia is:

(a) insert a sample probe in the vehicle exhaust outlet
(b) with the engine idling at normal operating temperature, apply the brakes and engage drive
(c) initiate the measuring cycle on the DPM measuring instrument
(d) after 20 seconds fully depress the accelerator
(e) after a further 20 seconds release the accelerator pedal
(f) after a further 20 seconds of idle running, stop the test and disengage drive.

The chart below summarizes the test's power profile.

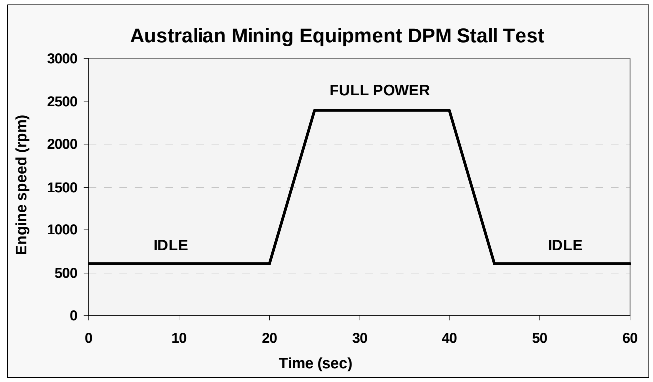


Figure 4. Time-Power Sequence of Australian Mining Equipment DPM Stall Test.

The test result is a simple (unweighted) average of the DPM concentration over the complete 60 seconds.

As the test takes only one minute to complete and requires no preparations other than ensuring the engine is at normal operating temperature, it can be easily merged into routine maintenance schedules.

Using instruments specifically designed for mines DPM testing, engine maintenance personnel are increasingly checking exhaust particle levels as part of their normal scheduled servicing activities. The test results are used to trigger emissions-related maintenance and to validate the effectiveness of and repairs / maintenance performed.

New generation equipment can also provides some additional test data to assist in diagnosis of engine and fuel system problems.

7 Test Equipment

The central element of any DPM monitoring program is the equipment used to measure DPM concentrations. For this equipment to be used effectively as an industrial tool, it must have the following attributes:

- rugged construction
- simple operation
- low maintenance
- portable
- immediate result.

Until recently, visible smoke density has been measured to estimate particle emission levels, either by continuous measurement (light beam attenuation) or cumulative (optical analysis of soot on a filter). While these methods have proved to be useful, they do have limitations, either in their ability to monitor transient tests, or the range of DPM concentrations and particle sizes they are able to measure.

In addition, some additional data capture and analysis hardware may be required to determine a test result, adding to the complexity and time needed to complete a test.

To overcome these limitations, two technologies have emerged as useful methods for reliably and directly measuring PM concentrations in diesel engine exhaust.

7.1 Pressure Drop Method

Drawing a sample of diesel exhaust through a small filter and monitoring the pressure drop across the filter as particles build up on it surface, provides a simple and low-cost option.

Several studies have been completed to assess this method for measuring ambient coal dust levels as well as particles in raw diesel engine exhaust.

A recent study on the emission reduction benefits of diesel maintenance (*Davies, McGinn, 2005*) provided test data demonstrating good correlation between the SKC "Diesel Detective" pressure drop instrument and laboratory results for elemental carbon (EC) concentrations.

An extensive Australian research project to evaluate DPM measuring methods *(New South Wales Department of Primary Industries, Mine Safety Technical Services, 2004)* concluded that the pressure drop method used in the "Diesel Detective" represented a useful screening device which could conveniently be carried by maintenance personnel, due to its compact size and low weight.

7.2 Laser Light Scattering

Measurement of particle concentrations using laser light scattering photometry (LLSP) is a mature technology, with several instruments commercially available.

In 2002, Australia became the first country to introduce PM measurement into national on-road emission testing regulations. LLSP technology is universally used for this testing, as it provides continuous, second-by-second measurement of PM (in mg/m3), at low cost, with accuracy levels comparable to laboratory instrumentation.

Figure 5 shows the correlation between the laser method and laboratory filter results for 103 tests performed using several different transient dynamometer test cycle.

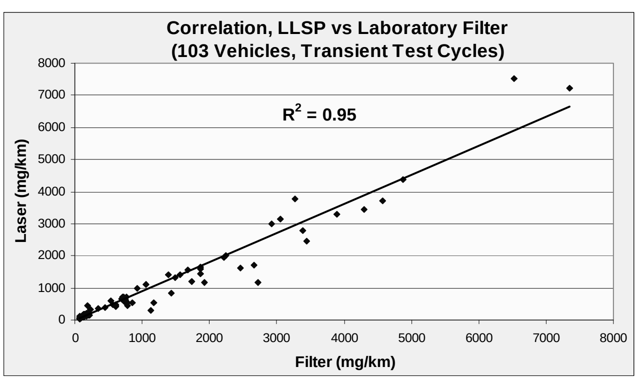


Figure 5. Correlation of LLSP and Laboratory Filter (Road Vehicles)

In the NSW research program *(New South Wales Department of Primary Industries, Mine Safety Technical Services, 2004)* good correlation with the NIOSH 5040 Method was observed

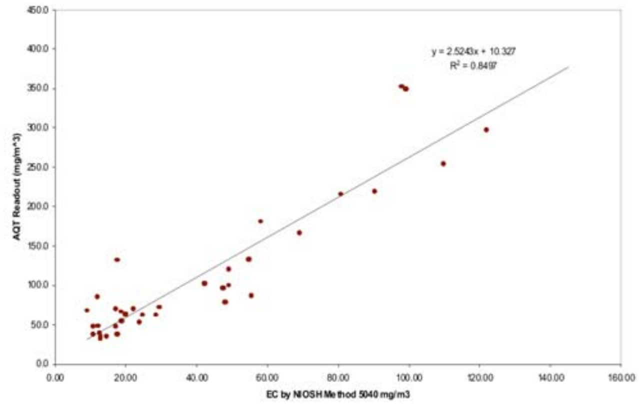


Figure 6. Correlation of LLSP and NIOSH 5040 Test Data

To meet mining industry's need for a rugged instrument capable of handling the hot, wet post-scrubber diesel exhaust encountered in underground operations, Australian company Air Quality Technologies (AQT), in conjunction with MicroCAD Australia developed a portable, LLSP instrument to meet this challenge.

AQT's first generation instrument has since been adopted as the de facto standard for DPM measurement by almost all the underground coal mines participating in Queensland's DPM management program for underground coal mines.

Responding to field experience and customer feedback, in 2007 MicroCAD Australia developed a completely new DPM detector sub-system.

The new hardware provides a similar measuring capability as the older system, but has much greater tolerance to contamination. Importantly, daily calibration checks can be performed on site in just a few seconds.

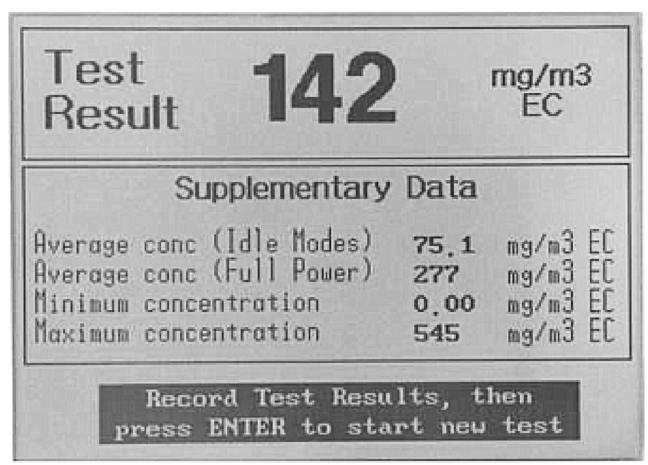


Figure 7. Test Result Screenshot - MicroCAD / MAHA DPM Instrument

On the software front, MicroCAD has also developed a completely new, interactive user interface to guide the operator through the standard 60-second test cycle.It also reduces operator input to a single push-button and at the completion of the test cycle automatically delivers a fully processed result in mg/m^3 of elemental carbon, together with key diagnostic information (see Figure 7 above).

All the operator has to do is press one button to set up the test and auto-zero the instrument, then press the same button once again when ready to start the test. The instrument signals, using a flashing light and on-screen instructions,, when to apply full power and when to back off to idle.

Data processing and result generation is performed automatically at the end of the 60 second test, without further input from the operator.

This new technology now forms the basis of the new MPM-4M Diesel Particle Measuring System from MAHA Maschinenbau – one of the world's leading manufacturers of vehicle safety and emission test equipment.

8 DPM Reductions from Maintenance

Evidence from mining and on-road vehicle maintenance studies has consistently demonstrated the benefits of effective, emissions-focused maintenance.

Interestingly, many of the most basic (but too often overlooked) maintenance tasks can deliver very large reductions in DPM levels. Given also that the dirtiest engines generally provide the largest absolute reductions, it can be seen that regular engine monitoring coupled with outcome-measured maintenance and repairs can make a very significant contribution to any DPM reduction strategy. Table 1 illustrates some case studies (*Davies, McGinn, 2005*)

Table 1. Effect of maintenance on raw exhaust EC emissions

Engine type	**Raw exhaust EC (mg/m^3)**		**Maintenance Performed**
	Before	**After**	
KIA 6-247	**139**	**46**	Cleaned exhaust scrubber tank
KIA 6-247	**131**	**40**	Cleaned exhaust scrubber tank
KIA 6-247	**102**	**61**	Replaced injectors, cleaned scrubber tank & intake system
MWM D916-6	**159**	**71**	Replaced injectors
KIA 6-247 (s/charged)	**155**	**75**	Replaced intake air filter
Cat3304	**166**	**54**	Replaced injectors
Perkins 1006.6	**75**	**44**	Retarded timing, cleaned air intake system
KIA 6-247	**206**	**80**	Cleaned flame trap, reduced fuel

The average DPM reduction from applying effective maintenance to the above engines is 57%.

Rio Tinto's Kestrel Mine in Queensland has been at the forefront of DPM measurement as an engine maintenance tool. The following graph (Figure 8, courtesy of Darrell Grant) shows the progressive downward trend in emission levels achieved over two years of monitoring and using test results as a trigger for maintenance.

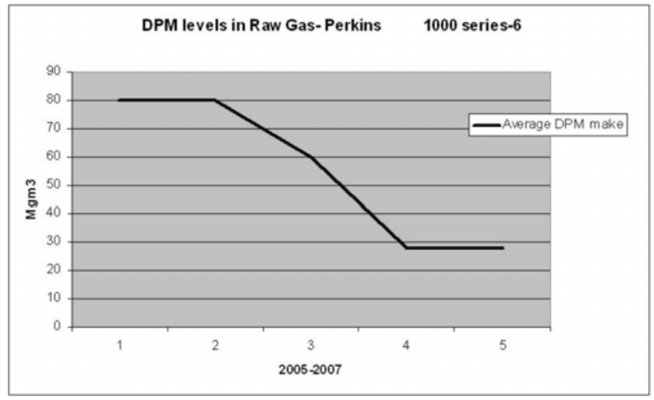


Figure 8. 64% Reduction in DPM over 2 yrs from Perkins Engines at Rio Tinto's Kestrel Mine, Queensland.

9 Conclusions

New DPM exposure regulations will require urgent action to improve the emissions performance of diesel engines used in underground mines.

Enhanced ventilation strategies, cleaner fuels and new technology engines will all play a part.

In the short to medium term, it is likely that improved, emissions targeted maintenance, has potential to deliver much of the required DPM reductions.

New technologies now allow quick and accurate monitoring of diesel engine performance, and can be used not only to trigger maintenance, but also to validate the effectiveness of any maintenance and repair work carried out.

References

New South Wales Department of Primary Industries, Mine Safety Technical Services, 2004. Methods for Measuring Diesel Particulate Matter from Underground Mining Equipment, (Ellis, Davies *et al*)

Davies, B., McGinn, S., 2004. The Effect of Maintenance of Diesel Engines on Particulate Generation, *International Occupational Hygiene Association 6th International Scientific Conference Pilanesberg National Park North West Province, South Africa 19 - 23 September 2005*