Diesel Particulate (Soot) Exposures and Methods of Control in some Australian Underground Metalifferous Mines

Alan Rogers
Alan Rogers OH&S Pty Ltd
Brian Davies
AEHS Pty Ltd

QUEENSLAND MINING INDUSTRY HEALTH & SAFETY CONFERENCE 2001

ABSTRACT

The health issues of exposure to diesel particulate (soot) have been the subject of scientific debate for some considerable period and have resulted in the recent promulgation of Exposure Standards by some overseas countries. Studies from Canada and the USA indicate that the airborne levels of diesel particulates in metaliferrous mines are generally well in excess of these new exposure standards. Monitoring conducted by the authors at six (6) Australian underground metaliferrous mines also indicate some exposures to be higher than the standards and in most instances above the levels previously reported within the Australian underground coal industry. A comparison of Australian exposure levels to overseas data from similar operations, as well as a rank the data against overseas current or proposed exposure standards, is discussed. An overview of control technologies currently available within the metaliferrous mining industry is also provided. Given the dependence of the underground metaliferrous mining industry on diesel-powered equipment, the flow-on for implementation and compliance with such standards will most likely have a significant impact on Australian operations.

DIESEL PARTICULATE MONITORING METHODS

Diesel emissions are composed of a complex mixture of particulates and gases. The gaseous component consists of water vapour, oxides of carbon (CO, CO_2) oxides of nitrogen (NO, NO_2, N_2O_4) volatile organic compounds arising from the combustion process and the unreacted gaseous components from air such as nitrogen. The particulate or 'soot" component is a complex mixture consisting of solid carbon cores produced during combustion together with a range of adsorbed organic material which can constitute up to 65% of the mass. More than 90% of these carbon particles are respirable, with aerodynamic diameters of 1 micrometre or less and are therefore capable of entering the deepest regions of the lungs.

Due to this small particle size, diesel particulate can be readily separated from the mineral dust aerosol found in mine atmospheres using a two-stage separator to firstly collect the respirable size fraction and then split it into a sub and super micron fractions. The sub micron fraction contains more than 85% of the diesel soot, and is then subject to gravimetric analysis (DPM mg/m^3) or carbon analysis in a thermal optical furnace. By ramping the optical furnace temperature, various species that make up the total carbon content of the aerosol (TC mg/m^3) such as carbonate, organic (OC mg/m^3), elemental (EC mg/m^3) can be separated and quantified (Rogers 1996).

Although sampling methodology and carbon species analysis has been standardised and adopted into US legislation, there are only a small number of laboratories that conduct such analysis in the USA (NIOSH 1995, MSHA 2001). The single Australian sampling and analysis services is provided as part of the research associated with the Joint Coal Board Health and Safety Trust.

HEALTH EFFECTS OF DIESEL PARTICULATES AND EXPOSURE STANDARDS

The health effects of exposure to diesel emissions have long been debated. Animal studies involving long term exposures to very high concentrations of diesel particulates produce a range of cancerous and non-cancerous pulmonary effects such as chronic inflammation and restrictive and obstructive lung function patterns. However human epidemiological studies on miners do not provide strong or consistent evidence for such chronic, non-malignant effects. The evidence of an association between human cancers and diesel particulates is inconclusive with some studies indicating an increased risk and others indicating no additional risk. Of particular interest to the mining community is the study of NSW coal miners that did not show any increased risk of lung cancer even though the miners were exposed to a combination of coal dust and diesel particulates (Kirby 1995).

Various health and mining authorities have seen fit to develop exposure standards for diesel particulates. The recommended general industry standard set by the US ACGIH TLV, is Diesel exhaust particulate 0.050 mg/m^3 measured as the submicron fraction (Notice of Intended Change for 2000) (this is ~ equivalent to Total Carbon measurement)

US MSHA have on the statutes a Proposed Rulemaking of 0.16 mg/m^3 Total Carbon for metal and non-metal mines. There is no nominal exposure value for coal mines but a requirement for the use of control technology to effect a 95% reduction of diesel particulates in raw exhaust levels.

Regulations for NSW metaliferrous mines list a diesel soot limit of 2 mg/m^3 as measured using specific methods, however our experience is that at such levels extreme eye and respiratory tract irritation would be experienced.

The NSW Mineral Council on the basis of our research in coal mines have recommended so as to minimise irritation a level of 0.2 mg/m^3 DP (~ 0.17 mg/m^3 Total Carbon).

EXPOSURE LEVELS IN AUSTRALIAN METALIFERROUS MINES

Surveys of 6 underground metaliferrous mines and one tunnelling operation have been undertaken and the results summarised in Table 1.

Mine	DPM mg/m^3	EC mg/m^3	TC mg/m^3
1. Cu extraction	0.11 - 1.30	0.042 – 0.372	0.112 – 0.572
2. Pb/Zn development	0.19 - 0.75	-	-
3. Pb/Zn development	0.12 – 0.38	0.060 – 0.190	0.115 – 0.293
4. Pb/Zn extraction	0.07 – 0.56	0.021 – 0.265	0.060 – 0.456
5. Pb/Zn extraction	0.05 – 0.60	0.010 – 0.180	0.050 – 0.420
6. Pb/Zn extraction	0.16 – 0.57	0.017 – 0.418	0.130 – 0.532
7. Sandstone tunnel	-	0.010 – 0.210	0.050 – 0.320

Table 1

There is considerable variability in the exposures dependent on working conditions and machinery type both within each mine and also for from mine to mine. The higher exposures usually occur when there is large machinery working hard and also in situations such as poor roads, steep inclines, long hauls with heavy loads, multiple vehicle activity and or when there is poor engine maintenance.

We have found similar trends of exposure in the NSW and Queensland underground coal mines, however in underground metaliferrous mines the exposures are much higher mainly due to the larger engine sizes and the loads carried.

Due to the through ventilation system used in the metaliferrous industry, many other mine workers not directly involved with heavy diesel machinery but who are inbye have the potential to be exposed to high levels of diesel particulate.

A fair proportion of the exposures in the Australian mines surveyed above are in excess of the MSHA standard of 0.16 mg/m^3 TC. Australian mines are not alone in producing high exposures, US and Canadian underground metal and non-coal mines report a range of exposures from 0.25 – 1.7 mg/m^3 DPM.

CONTROL TECHNOLOGIES

The use of technologies to control diesel particulate levels in the Australian underground metaliferrous mining industry has been limited. In general the industry has placed substantial reliance on gas testing of raw exhaust, ventilation and personal protective equipment (PPE) as the means for controlling diesel particulates. Some contemporary equipment is fitted with regenerative soot traps. Reliance on these two measures of ventilation and PPE is understandable as early generation ceramic filters were tried at substantial cost with less than favourable results. One other control technology, which has been the subject of much debate within the metaliferrous industry, is fuel quality. Again, some sections of the industry have seen the introduction of low sulphur fuels as the answer to the problem, and while it offers some benefits, it is by no means the ultimate solution.

A recent study by the US Department of Labour (MSHA 1997) on the practical ways to reduce exposure to diesel emissions (including particulates) in mining identified a number of important parameters. Many of these have been evaluated within the Australian metaliferrous mining industry with the following outcomes.

- **Low Emission Engines**

  Improvements in engine design over the last decade have led to packages with more homogeneous fuel mixtures and more complete combustion. Electronically controlled engines offer a system whereby the amount of fuel injected into the cylinders is exactly metered for the load on the engine. This has the benefit of reduced fuel consumption and lower emissions. The extent of lower emissions has been demonstrated by an exercise conducted at a central Queensland metaliferrous mine in which trucks fitted with normal and electronic controlled engines hauling up a decline were monitored. The results (Table 2) indicate a reduction of approximately 31-43% depending on the duty cycle of the day. This exercise was conducted over three days and involved 11 trucks.

Engine Type	Average Elemental Carbon Conc (mg/m^3)	% Reduction
Caterpillar	0.14 – 0.18	-
Detroit	0.08 – 0.125	31 - 43

Table 2

  This data is consistent with similar research from Canada where reductions of up to 50% have been reported.

- **Low Sulphur Fuel, Fuel Additives and Alternate Fuels**

  Fuel quality has been the subject of many debates within the Australian mining industry (both coal and metaliferrous) for many years. The first controlled evaluation of different fuel types was conducted by AMDEL in the 1980's, however this project used a bus engine tested on a dynamometer, and was the subject of some criticism (Robinson 1990).

  An extensive evaluation of a number of fuels at Tower Colliery (Pratt 1995) over a six-month period in a surface test tunnel, highlighted the relationship between diesel particulate and sulphur content of the fuel. The results indicated a direct linear relationship between particulate emissions and fuel sulphur content. A further exercise has been undertaken by ACIRL (Humphreys 1998). Following controlled testing at Tower Colliery an onsite trial was conducted at a lead/zinc mine in the north of Western Australia. The use of a low sulphur fuel resulted in reductions of up to 54% when compared to the previous high sulphur fuel imported from Asia.

  From this and other published research it is possible to state that low emission fuels:

  - reduce diesel particulates
  - do not lead to wear problems if well formulated
  - reduce irritation
  - are produced by all oil companies, and
  - generally attract a cost premium.

  Some states have already legislated the introduction of low sulphur fuel and it is stated Federal Government policy that this will occur.

  A variety of fuel additives are available to reduce emissions. For example, cetane improvers increase the cetane number of the fuel, which may reduce emissions and improve starting. Oxygenated additives increase the availability of oxygen needed to oxidise hydrocarbons in the fuel. Detergents are used primarily to keep the fuel injectors clean.

Dispersants or surfactants prevent the formation of thicker compounds that can form deposits on the fuel injectors or plug filters. Lubricity additives are similar to corrosion inhibitors and are frequently added to fuel by petroleum producers. There are also stability additives that prevent the fuel from breaking down when it is stored for long periods of time. It is important to realise that the use of additives may result in emissions that are potentially more harmful (ie increased biological activity) than the emission from pure fuel. To this end some countries have introduced registration systems to ensure that no further harmful agents are released into the mine environment. A similar approach is being adopted by some regulatory agencies in Australia.

The quest for alternate fuels is endless, with many proposals being considered over the past few years. Biodiesels using treated crop oils have been developed in the USA, however these often add unpleasant aromas to the mine atmosphere as is the case with waste rape seed oil which produces a "fish and chip shop" smell. To date a cost effective low emission substitute for diesel fuel has not been identified, however the process to develop such products continues.

Good quality fuel offers significant benefits but it is by no means the ultimate solution. Monitoring exercises within Australia have demonstrated that diesel particulate levels can be elevated within those mines using low sulphur fuel as a result of poor ventilation, inadequate maintenance or inappropriate work practices.

- **After Treatment Devices**

After treatment devices fall broadly into the following categories.

- ***Fume Diluters***

Experience overseas has shown that these devices offer only a cosmetic solution as the total mass of particulate generated into the mine atmosphere remains unchanged. It is interesting to note that prior to 1999 one Canadian province regulated fume diluters as the only acceptable after treatment technology.

- ***Catalytic Converters***

While catalytic converters offer a 95% reduction in carbon monoxide and hydrocarbons, they provide little impact on oxides of nitrogen and particulates.

Flow-through catalytic purifiers are an extension of the above concept and consist of a ceramic monolite substrate coated with a precious metal catalyst. The US EPA has certified these units as 25% particulate reduction on certain types of buses. Testing within Australia has confirmed these results on engines up to 100 kW, which suggests they may offer a useful control technology for light duty vehicles.

- ***High-Efficiency Filtration***

The development of ceramic regenerative filters has continued over the last decade resulting in units that are smaller in size and regenerate at lower temperatures. While reductions in particulates of 85-95% can be achieved, problems still exist due to durability, regeneration issues, maintenance and cost.

- **Ventilation**

Ventilation has been the main process by which diesel emissions (including particulates) have been managed within the metaliferrous mining industry. There is no question that the application of good ventilation practices is essential. Research in the Australian coal industry has indicated that the prescribed ventilation rates are suitable for control of exhaust gases, however up to two times the level of those presently in use, may be required to control diesel particulate levels so as to reduce irritation and to meet the proposed overseas exposure limits.

Little research has been conducted in the underground metaliferrous mining industry to establish if similar ventilation requirements would be necessary.

While adequate ventilation is a necessity to assist in the control of diesel particulates, control at the source (ie the engine package) is critical.

- **Use of Enclosed Cabins**

The use of air-conditioned cabins on all diesel equipment presents a cost-effective means of reducing operator exposure to diesel particulates. Monitoring of exposures inside and outside of cabins has demonstrated significant reductions (Table 3), however poorly maintained filter systems, door seals and the practice of operators driving with open windows negates this benefit (Table 4).

Location	DP (mg/m^3)
Outside Cabin – Mucker	0.79
Inside Cabin – Mucker	0.11

Table 3

Location	DP (mg/m^3)
Outside Cabin – AD40	0.50
*Inside Cabin – AD40	0.31

* window open

Table 4

Our experience in monitoring metaliferrous mines is that air-conditioned cabs provide varying filtration efficiencies (typically 30-87%) which are dependent on a combination of the design and condition of the filtering system, the proportion of recycled air and the quality of the door and window seals.

- **Maintenance**

Evidence, both in Australia and overseas, strongly indicates that routine preventative maintenance reduces the level of workforce exposure to diesel particulate. Some organisations are using underground diesel test stations to monitor for changes in engine parameters, which affect emissions (both gaseous and particulate as they are linked). Such systems are only effective as long as maintenance engineers use the data on a timeline basis (ie look for changes on a routine basis). This requires resources but does highlight potential problems at the maintenance bay prior to them occurring at critical times and causing higher emission levels followed by delays in the mining operation.

Perhaps the most dramatic evidence of this has been demonstrated in the coal industry where the raw exhaust diesel particulate level was measured pre and post maintenance, resulting in a 55-71% reduction (Table 5).

	Total Carbon g/kWhr
Pre Maintenance	0.84 – 1.4
Post Maintenance	0.38 – 0.40

Table 5

The ability to adequately measure the level of diesel particulate in the raw exhaust of engines has only recently been demonstrated (Davies 2000) and offers engineers a valuable diagnostic tool. At present the instrumentation required for this process is complex being similar in nature to the method used for measuring environmental diesel particulate, however alternative surrogates are currently under investigation within Australia.

- **Work Practices and Personal Protective Equipment**

  Reliance on respiratory protection to control worker exposures to diesel particulates cannot be condoned, however practical experience would suggest that such devices will need to be used to control some situations. One example that has been experienced occurs when loaders are operated on "remotes" to load from long stopes. In such cases the operator stands to the rear and one side of the unit to load and then enters the cabin to drive to the discharge point. Monitoring of an operator's location, (ie inside cabin and at designated remote operation point) indicated a significant increase in exposure when the operator exited the cabin to operate the loader in loading mode (Table 6).

Location	DP (mg/m^3)
Insider Cabin – Loader	0.27
Remote Operation Point	0.52

Table 6

Work practices (eg aggressive driving, idling engines) have been demonstrated to increase the level of diesel particulate in the mine atmosphere.

RESEARCH

The largest research programme within the underground mining industry is being undertaken in Canada via their "Diesel Emissions Evaluation Program" (DEEP). DEEP was formed in April 1997 with funding of CAD$2.3 million as a joint industry-labour-government consortium to assess technologies for reducing diesel particulate matter in the metal/non-metal underground mining industry. Projects currently underway include; Control Strategies for the Mining Industry, Biodiesel Research, Preventive Maintenance, Light Duty Vehicles, Comparison of DPM Sampling Methods, and Filter Trap Field Tests.

Research on this scale does not appear to be occurring outside Canada, however significant interest is being generated within Europe where statutory requirements in regard to diesel particulates during tunneling are rapidly being introduced. Although Australia has a major underground metaliferrous mining industry, limited research has occurred and little is proposed. This exposes Australian operations to overseas trends potentially resulting in controls inappropriate to the Australian environment or work practices. The Australian underground coal mining industry has been very proactive and has been well placed to challenge overseas measures that were not appropriate to Australian conditions.

More research within the Australian metaliferrous mining industry in respect to diesel particulates is required if employee exposures are to be reduced to overseas proposed standards in a cost effective manner.

REFERENCES

Davies, B., Application of an Elemental Carbon Analyser to the measurement of particulate levels from diesel vehicles. ACARP Report C7014, May 2000.

Humphreys, D., Chrzanowski, D., Muller, S., Tail, R., O'Beirne, T., The Effects of Diesel Fuel Quality on the Exhaust Emissions of Underground Mining Engines. ACARP Report No. C3081, June 1998.

Kirby W, Joint Coal Board Cancer Study, Abstract 91, The Second International Conference on the Health of Miners, Pittsburgh, November 1995

NIOSH Method 5040, Elemental Carbon (Diesel Exhaust) Manual of Analytical Methods, Draft 1/15/95

Pratt, S., Grainger, A., Todd, J., Meena, G., Rogers, A., Davies, B., Evaluation and Control of Employee Exposure to Diesel Exhaust Emissions in Underground Coal Mines. ACARP Report No. C3080, May 1995.

Robinson, R.R, Demaria, S, and Mitkas, J., Toxic Emissions Levels from Coal Mine Diesel Engines as to Diesel Fuel Quality, NERDDC Grant Report No. 898, February 1990.

Rogers A and Whelan W, Elemental Carbon as a Means of Measuring Diesel Particulate Matter Emitted from Diesel Engines in Underground Mines, Proceedings of Annual Conference Australian Institute of Occupational Hygienists, December 1996

US Department of Labour 1997, Practical ways to reduce exposure to diesel exhaust in mining – a toolbox. US Department of Labour, Mine Safety and Health Administration.

US Department of Labour Mine Safety and Health Administration, Diesel Particulate matter Exposure of Underground Metal and Nonmetal Miners 30 CFR Part 57, Federal Register, 66, No 13, January 19, 2001.