Diesel Particulate Matter in Queensland's underground metal mines

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In January 2005, Simtars commenced a diesel particulate matter (DPM) monitoring program of underground metalliferous mining operations in Queensland, with the aim of establishing exposure levels across a range of different work groups and areas. At the commencement of the monitoring program, there were 12 underground metalliferous mines operating in Queensland, however several of these were excluded from the program for various reasons including the closing down / winding down of underground operations. At the conclusion of 2005, sampling had been undertaken at a total of nine sites. The commodities being mined at the nine sites sampled was varied, but included gold, copper, silver, lead and zinc.

The program was predominantly focused on the measurement of operator exposures and as such the majority of the samples collected were personal (i.e. worn by the operator of interest). Some static (or fixed position) monitoring was also conducted in conjunction with the personal sampling. However as static samples are not indicative of actual personal exposures, they are not included or discussed in this paper.

In addition to the monitoring of workers, some basic information was gathered at each of the sampled sites, to ascertain the extent of controls and/or management systems used to reduce the potential for operator exposure to diesel particulate matter while working underground.

Background

Prior to the conduct of this monitoring program, there has been very little, if any, monitoring or assessment conducted to determine the extent of diesel particulate matter exposures to underground workers in the Queensland metalliferous mining industry. Some work has been conducted over the past few years in assessing exposures in the underground coal mining industry, but due to the significant differences in mining methods, the equipment used, ventilation and mine design, this data is not applicable to the metalliferous mining environment.

The monitoring program adopted required the collection of a large number of samples over a short period of time at each site, with the aim of providing an indication of the magnitude of personal DPM exposures for each site, and the underground metalliferous mining industry in general.

Exposure standards

To use sampling data to determine compliance or health risk and the potential for adverse health effects from DPM, reference needs to be made to an established exposure standard or guidance level. At this time there is no published occupational exposure limit for DPM in any Queensland legislation, nor does a national standard exist.

In 1999 the NSW Minerals Council (1999) proposed an industry best practice exposure standard of 0.2mg/m^3 for submicron DPM (equivalent to 0.16mg/m^3 Total Carbon, or 0.1mg/m^3 Elemental Carbon) to minimise the irritant effects of exposure. However, they also stated that there was a lack of valid epidemiological data to suggest whether exposure, at or below this level, would also prevent the incidence of carcinogenic effects.

Davies and Rogers (2004) in their document produced for the Australian Institute of Occupational Hygienists (AIOH), also supported reduction of exposures to below 0.2mg/m^3 for submicron DPM (equivalent to 0.1mg/m^3 Elemental Carbon) to reduce the irritant effects of exposure.

To date, only the Western Australia mining regulatory body has promulgated an exposure standard (albeit provisional) of 0.1mg/m^3 measured as Elemental Carbon (Department of Consumer and Employment Protection 2005), based on the AIOH publication produced by Davies and Rogers. Some mining companies have taken it upon themselves to identify corporate exposure standards for operator exposure to DPM, with one example being BHP Billiton (2005) who has specified a limit of 0.2mg/m^3 measured as DPM, or 0.1mg/m^3 measured as Elemental Carbon.

The Mine Safety and Health Administration (2005) in the United States proposed an interim exposure standard of 0.4mg/m^3 measured as Total Carbon, which was later revised to a comparable but more accurate measure of 0.308mg/m^3, measured as Elemental Carbon. On 20 May 2006 the final rule was published and is to be phased in over a two year period. From 20 May 2006 the interim exposure standard of 0.308mg/m^3 of Elemental Carbon will come into force, followed by a further reduction to 0.350mg/m^3 Total Carbon (equivalent to 0.270mg/m^3 elemental carbon) on 20 January 2007. The final limit of 0.160mg/m3 Total Carbon (equivalent to 0.123mg/m^3 Elemental Carbon) will become effective on 20 May 2008.

Based on the above information, an exposure limit of 0.1mg/m^3 measured as Elemental Carbon was used as the criteria for compliance for the monitoring program. The more accurate measure of Elemental Carbon was used, as it is not subject to the same interferences from non-diesel combustion sources, as measures of Total Submicron DPM, Total Carbon or Organic Carbon.

No adjustment of the exposure limit was made where the operators at the sampled site worked extended shifts. This is based on the absence of a generally accepted exposure standard for diesel particulate that has a sound epidemiological, or dose response basis for its setting.

Sampling Strategy
Simtars, in consultation with Queensland Government representatives, identified 12 occupational groups in the underground mine environment that were of particular interest in terms of exposure to diesel particulate matter. All operators working within these occupational groups are considered to have similar exposures and were identified principally by activities performed. Descriptions of the final list of Similar Exposure Groups (SEGs) identified for the monitoring program are detailed in Table I below:

Table I – Similar Exposure Groups (SEG)

SEG No.	SEG Id	Activity description
1	Nipper	General duties, store person.
2	Service crew / timberman	Extension of mine services (ventilation, water, compressed air, power).
3	Mobile maintenance	Works all over mine servicing vehicles and conducting insitu repairs.
4	Loader operators	Also known as LHD (load haul dump units or boggers). Production and development 'bogging' of blasted ore to trucks and or stockpiles.
5	Charge-up crew	Charging and firing of production and development headings.
6	Drill operators	Includes jumbos and cable bolters (development drilling and strata support), and diamond drilling (exploration).
7	Truck drivers	Carting of ore and/or waste rock underground and to the surface.
8	Crusher operators	Underground crusher operators.
9	Shot-creters	Spraying of concrete onto walls / ceilings following bolting.
10	Supervisor	All over mine site, inspecting / allocating tasks.
11	Locomotive operator	Drives diesel powered locomotive used to move large amounts of ore within the mine.
12	Workshop fitter	Vehicle maintenance / service person based in underground workshop.

Number of samples collected
A determination of the number of samples to be collected for each SEG, at each of the locations was made with reference to the NIOSH Occupational Exposure Sampling Strategy Manual (Leidel et al 1977), in particular Table A-2 in Technical Appendix A. This table identifies the sample size (n), for an exposure group (N), to ensure with 95% confidence that the monitoring program will include at least one worker in the top 10% of exposures.

Prior to the conduct of monitoring at each participating site, it was requested that information be provided to Simtars on the number of employees working underground and the types of activities performed. This information was as the basis for assigning a particular operator to an SEG. The target number of samples (n) that was to be collected during the time on-site was determined from NIOSH Table A-2, and used the number of operators representing the particular SEG, working each shift, as the basis for the exposure group (N).

Whilst every attempt to was made to ensure that this was the case, sampling equipment failure, operational changes and the unavailability of workers meant that this was not possible at several sites. In some instances however, it was possible to collect a larger number of samples for a particular SEG than was initially specified.

A total of 288 personal DPM samples were collected throughout the monitoring program. A total of 13 samples were declared invalid due to either equipment factors (failure, damage, etc) or operator factors (removal of monitoring device or departure from site). The number of valid samples collected at each of the sites, by SEG, is identified in Table II below:

Table II – Valid DPM samples by SEG and Site

SEG No.	SEG Id	Number of samples									
		Site 1	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**	**Site 8**	**Site 9**	**Total**
1	Nipper	6	1	3	2	3	6	2	0	3	**26**
2	Service crew / timberman	4	1	3	2	3	6	3	2	3	**27**
3	Mobile maintenance	6	1	3	2	5	3	2	3	0	**25**
4	Loader operators	6	3	5	4	4	12	3	6	5	**48**
5	Charge-up crew	6	0	3	4	3	2	0	3	3	**24**
6	Drill operators	6	1	0	4	5	6	3	3	9	**37**
7	Truck drivers	6	0	7	5	6	4	2	6	3	**39**
8	Crusher operators	4	0	0	0	0	0	0	0	0	**4**
9	Shotcreters	2	0	0	2	0	0	0	3	0	**7**
10	Supervisor	0	1	3	3	3	5	3	3	3	**24**
11	Locomotive operator	0	1	0	0	0	0	2	0	0	**3**
12	Workshop fitter	0	0	0	0	0	4	3	0	0	**7**
	Other	0	0	0	0	0	2	1	0	1	**4**
	TOTAL	**46**	**9**	**27**	**28**	**32**	**50**	**24**	**29**	**30**	**275**

As can be seen in Table II, not all similar exposure groups have valid samples collected at each site. This is due to a variety of factors including:

- unavailability of target operator at time of sampling
- SEG not existing at specific site
- sampling equipment failure / damage.

Sampling method

The method of distribution and retrieval of samples from operators varied from site to site. In many instances samples collected were not full shift, but were assumed to be representative of the operator's normal activities. The results of diesel particulate matter analysis were used to calculate time weighted average concentrations encountered by operators during the sampled work shift, allowing comparison with relevant regulatory and / or health based limits.

Diesel particulate samples were collected using SKC's Diesel Particulate Matter (DPM) cassette, part no. 225-317. A cyclone was fitted to the inlet of the DPM cassettes during the sampling process to reduce the potential for larger particles to congest the impactor. Air was drawn through the sampling train using a constant flow sampling pump set at a rate of 2.0L/min. Samplers were calibrated prior to, and following sampling, to ensure flow rates were +/- 5% of the set flow point. Sampling pumps were fitted to the operator's belt and connected via flexible tubing to the sampling head, located within the operators breathing zone.

The sampled diesel particulate cassettes and field blanks were shipped to the Coal Services Health laboratory in NSW, where thermal-optical analysis was performed following the principles of NIOSH Method 5040 (NIOSH 2003). The weight of Organic Carbon (OC), Elemental Carbon (EC) and Total Carbon (TC), expressed as micrograms per filter, were reported to Simtars. All results received, were blank corrected prior to interpretation and evaluation.

Data summary

Raw monitoring data

The number samples collected that were in excess of the 0.1mg/m^3 exposure limit (measured as Elemental Carbon) are detailed in Table III below, arranged by Similar Exposure Group and Site. Where there was no sample collected for a particular exposure group at a particular site, a dash has been inserted into the corresponding cell to differentiate between the absence of a sample and the absence of a sample in excess of the limit.

Table III – Number of samples in excess of 0.1mg/m^3 Elemental Carbon exposure limit by SEG and site

SEG No.	SEG Id	Number > 0.1mg/m^3									Total	% > 0.1 mg/m^3
		Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9		
1	Nipper	2	0	0	0	0	0	0	-	0	**2**	**8**
2	Service crew / timberman	2	0	0	0	2	2	0	0	2	**8**	**30**
3	Mobile maintenance	0	0	0	0	0	0	0	1	-	**1**	**4**
4	Loader operators	2	0	4	1	0	2	0	3	1	**13**	**27**
5	Charge-up crew	3	-	0	0	3	0	-	0	0	**6**	**25**
6	Drill operators	1	0	-	1	3	0	0	0	3	**8**	**22**
7	Truck drivers	1	-	1	2	0	0	0	1	0	**5**	**13**
8	Crusher operators	0	-	-	-	-	-	-	-	-	**0**	**0**
9	Shotcreters	2	-	-	1	-	-	-	2	-	**5**	**71**
10	Supervisor	-	0	0	0	0	0	0	0	1	**1**	**4**
11	Locomotive operator	-	0	-	-	-	-	0	-	-	**0**	**0**
12	Workshop fitter	-	-	-	-	-	0	0	-	-	**0**	**0**
	Other	-	-	-	-	-	1	0	-	0	**1**	**25**
	TOTAL	**13**	**0**	**5**	**5**	**8**	**5**	**0**	**7**	**7**	**50**	**18**
	% > 0.1 mg/m^3	**28**	**0**	**19**	**18**	**25**	**10**	**0**	**24**	**23**	**18**	**-**

A dash indicates that no samples were collected for this SEG at this site.

With the exception of Site 2 and Site 7 all sites had between approximately 10% and 30% of the personal samples collected in excess of the DPM exposure limit. It is pertinent to note that Sites 2 and 7 were not particularly large mines, or were 'winding down' operations and had a small or reduced diesel vehicle fleet operating at the time of monitoring.

Reference to the number of DPM exposure limit exceedances by SEG shows that only three groups had all of their exposures below the limit, namely, workshop fitters, crusher operators, and locomotive operators. The remaining groups all had between 4% and 71% of samples in excess of the limit. In each of these cases, with the exception of the loader and truck operators, workers would be likely to spend significant periods of time each shift working outside of air-conditioned vehicle cabins. In the case of the service and charge-up crews, and the shotcreters, this could also be in the presence of continuously operating diesel equipment (i.e. charge car, service IT or concrete sprayer).

Diesel emissions control and management

A brief review of the processes and procedures at each site, that had the potential to affect diesel particulate concentrations underground, identified that generally the management and control practices were very similar at each site.

With the exception of two sites, where the sulphur content of the fuel used was not known, all diesel fuel used underground was of a low sulphur type with a typical sulphur content of 0.05%.

Most sites used $0.04m^3$/sec/kW as the minimum design flow rate for underground workings, however, no formal procedures existed to permit / restrict the entry of vehicles into ventilated zones, based on minimum ventilation requirements (e.g. vehicle tag board system, etc).

It was indicated by maintenance personnel that all vehicles operated by people monitored as part of the program were fitted with catalytic converters; no vehicles were fitted with diesel particulate filters of any type.

Raw exhaust gas testing was performed at most sites, however intervals were quite varied, and while the results of testing were used to trigger engine maintenance events, it was indicated that specific maintenance targeting the reduction of DPM levels at the exhaust did not exist.

Statistical Analysis

The data was analysed using the American Industrial Hygiene Association (1998) IHSTAT data analysis spreadsheet. Analytical results that were less than the limit of detection were recorded in the calculations as 50% of the limit of detection. A summary of the log-normal parametric statistics for the monitoring program is detailed below in Table IV.

The Minimum Variance Unbiased Estimator (MVUE) was used as the estimation of the mean, while the Lands Exact 95% Upper Confidence Limit (UCL) was used for comparison with the exposure standard. The MVUE and its 95% confidence limits by SEG are also presented graphically in Figure 1.

Tests for log-normality / normality were also performed. Where a distribution was found not to be log-normal (an occupational exposure dataset is expected to be log-normally distributed), log-normal parametric statistics are still reported and it is considered that additional monitoring (as should be performed for all of the SEGs, particularly those with small sample sizes) should be performed to further clarify the exposure profile. In these three instances the log-normal analysis shows a slightly worse prediction of the exposure profile for the SEGs when compared to the normal analysis data.

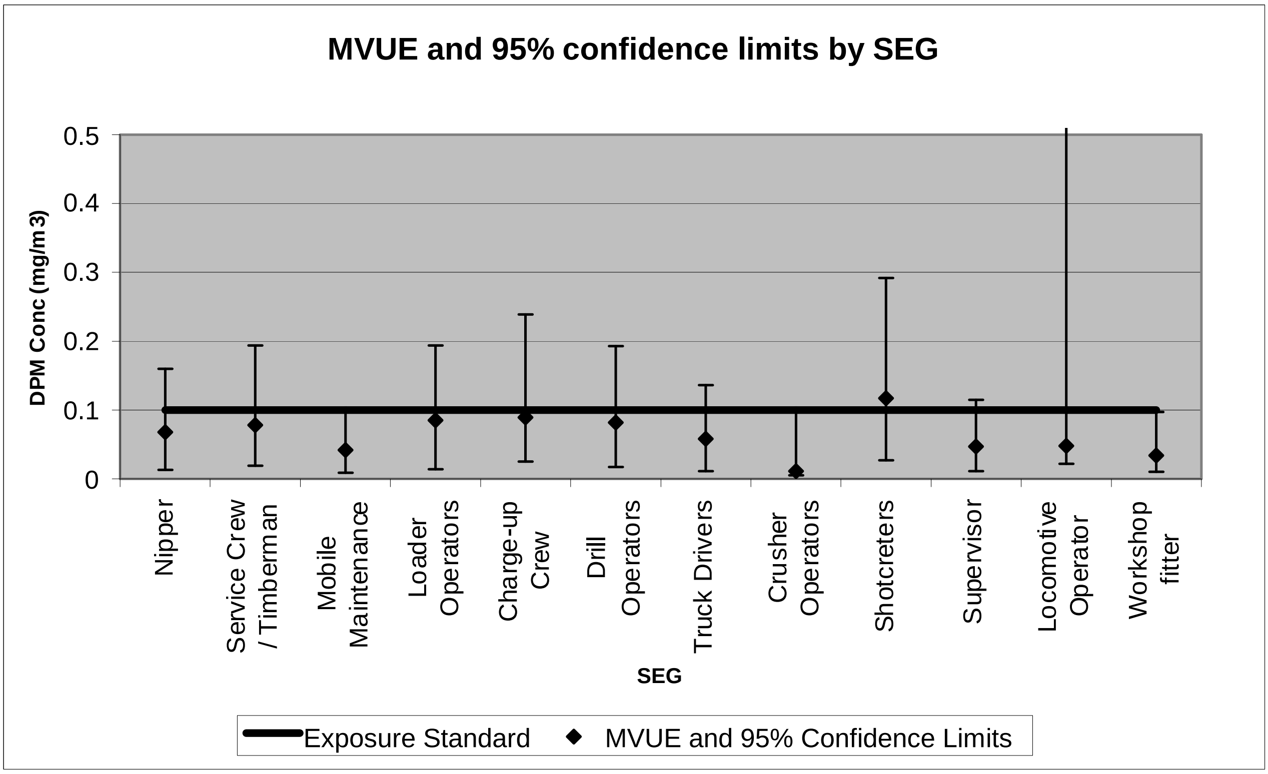
The percentage of samples that could be expected to be in excess of the exposure limit and the 95% UCL on that percentage, is also reported to describe the percentage of cases that it could be expected that operator exposures will be in excess of the limit, based on the data collected to date.

Table IV – Log-normal parametric statistics

Activity	SEG	Sample size	Log normal	Geometric standard deviation	Estimated arithmetic mean (MVUE) (mg/m^3)	95% UCL - Lands exact (mg/m^3)	Percent above exposure standard (%)	95% UCL on per cent above exposure standard (%)
Nipper	1	26	No	2.0	0.068	0.092	19	31
Service crew	2	27	No	2.3	0.078	0.116	24	37
Mobile mtce / UG workshop	3	25	Yes	2.0	0.042	0.057	6	14
Loader operator	4	48	Yes	2.2	0.085	0.109	28	37
Charge-up crew	5	24	Yes	2.6	0.089	0.150	28	42
Drill operators	6	37	Yes	2.3	0.082	0.111	26	37
Truck drivers	7	39	No	2.2	0.058	0.078	14	23
Crusher operators	8	4	Yes	2.0	0.011	0.088	<1	16
Shotcreters	9	8	Yes	1.6	0.117	0.175	56	77
Supervisor	10	24	Yes	2.2	0.047	0.068	9	19
Diesel locomotive operator	11	3	Yes	1.8	0.048	1.213	7	54
Underground workshop fitter	12	7	Yes	1.8	0.034	0.063	2	17

Shading indicates level in excess of DPM exposure limit of 0.1mg/m^3 (measured as Elemental Carbon)

Figure 1 – MVUE and 95% confidence limits.



The statistical analysis assumes random sampling. This means days, shifts, and personnel should be randomly selected for sampling. In addition all factors influencing exposure should remain constant during the sampling campaign. Any variation in the data is reflected by the geometric standard deviation (GSD). A large GSD indicates a significant variation in the dataset. The variation in the data may be due to the fact that sampling was conducted as a concentrated campaign over three to four and was therefore not perfectly random. There are other factors that will influence exposure that cannot be controlled by the investigator and are considered to include:

- differing activities and conditions between sites
- ventilation levels
- equipment type, age and condition
- operator factors (driving style)
- vehicle maintenance
- vehicle load conditions and operating duration
- work area arrangement (location of ventilation, location of worker with respect to ventilation and operating diesel equipment).

In order to limit the effect of these factors a longer sampling campaign is required, where the days and shifts are selected on a random basis. Therefore the analysis of the data is provided subject to these limitations.

Review of the statistical analysis shows that while the MVUE for 11 of the 12 Similar Exposure Groups is below the exposure standard of $0.1mg/m^3$ measured as Elemental Carbon (the shotcreters being the exception), at the 95% UCL, six of the groups have exposures in excess of the limit. These groups are:

- Service crew
- Loader Operators
- Charge-up crew
- Drill operators
- Shotcreters
- Loco operators

In some instances this interpretation is based on a relatively small sample size and further monitoring is necessary to better define the exposure profile.

Consideration of the percentage of samples that could be expected to be in excess of the exposure limit and the 95% UCL on this percentage, reveals that given the data collected, just over half of the SEGs could be expected to have more than 10% of exposures in excess of the exposure limit. However, at the 95% UCL, **all** SEGs will have exposures in excess of the limit in more than 10% of the cases. In some instances it is predicted that this may be as high as 54% for the Locomotive operators, and even 77% for the Shot-creters.

Conclusions

The statistical analysis suggests that operators across a number of Similar Exposure Groups, namely, the Service and Charge-up crews, Loader and Drill operators, Shotcreters and Locomotive operators, are potentially exposed to excessive levels of DPM at the 95%UCL on the mean. The 95% UCL on the potential number of samples in excess of the limit indicates that all SEGs will have at least 14% of exposures in excess of the limit and in one instance up to 77% of samples will exceed the limit. These hypotheses are subject to the limitations of the sampling program.

It would be expected that mine workers who spend significant periods of time exterior to vehicles fitted with sealed air-conditioned cabins, would be at a greater risk of exposure to DPM, although to what extent is dependant on some of the exposure influencing factors mentioned previously. The sampling results do support this with exposure groups such as the Service and Charge-up crews, Drill operators, Locomotive operators and Shotcreters all having exposures in excess of the limit at the 95% UCL Loader operators, while working from a sealed and air-conditioned cabin, are also at a greater level of risk, although this is not surprising, given that these vehicles do generate a large amount of diesel particulate when operating under load for extended periods, especially when reliance is placed on the ventilation and the integrity of the vehicles' cabin seals to reduce exposure.

Overall the monitoring programs data and its analysis suggests that personal Diesel Particulate Matter concentrations (measured as Elemental Carbon) in the Queensland metalliferous mining sector would not be acceptable from a compliance perspective, should the $0.1mg/m^3$ exposure limit be written into state legislation. The literature has reported a decrease in the irritant effects of DPM exposure by maintaining exposures below 0.1mg/m^3, thus from a health perspective, exposures are also unacceptable. Should diesel particulate matter exposure limits need to be adjusted for extended shifts in the future this has the potential to make the issue even more critical, especially in the mining industry where shifts up to 12 hours are frequently worked, and where the average number of hours worked each week can be as high as 60.

As the issue of exposure to DPM continues to emerge and regulators introduce legislation to address it, the mining industry will have to establish DPM emission management plans and embrace new technologies and fuel types in an effort to protect workers from related health effects.

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