The Magnitude of Diesel Particulate Matter in Underground Mine Workings: Advances in Real-Time Monitoring

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ABSTRACT

A real-time Diesel Particulate Matter (DPM) monitor has been developed on the basis of the successful National Institute of Occupational Health and Safety (NIOSH) designed Personal Dust Monitor (PDM) unit. The objectives of a recently completed Australian Coal Association Research Program (ACARP) study were to modify the PDM to measure the submicron fraction of the aerosol in a real-time monitoring underground instrument. Mine testing focused on use of the monitor in engineering evaluations to determine how conditions can be improved. Studies, including a selection during Longwall (LW) moves as described in this paper, demonstrated how DPM concentrations from vehicles fluctuate under varying ventilation and operational conditions. Correlation between the current SKC DPM measurement system and real-time DPM monitors were conducted and results from six mines show a correlation between elemental carbon (EC) and the new monitor DPM mass ranging from .51 to .81 with R^2 >.90. These differences are suspected to be due to variations from mine to mine in aspects such as mine atmospheric contamination, vehicle fleet variations, fuel type, engine maintenance, engine combustion efficiency, engine behaviour or interference from other submicron aerosol. Real-time monitoring readily reflects the movement of individual diesel vehicles and allows pin-pointing of high exposure zones such as those encountered where various vehicles work in areas of constrained or difficult ventilation. DPM monitoring approaches that have been available for some time based on shift average monitoring do not readily allow successful engineering evaluation exercises to determine acceptability of pollution levels. Identification of high DPM concentration zones allows efficient modification of mine ventilation, operator positioning and other work practices to reduce miners' exposures without waiting for laboratory analysis results.

KEYWORDS: Underground mine atmosphere pollutants. Real-time DPM, Total and Elemental Carbon.

INTRODUCTION

A real-time Diesel Particulate Matter (DPM) monitor has been developed on the basis of the successful National Institute of Occupational Health and Safety (NIOSH) designed Personal Dust Monitor (PDM) unit. The objectives of recently completed Australian Coal Association Research Program (ACARP) study (Gillies and Wu, 2008) has been to finalise the design of a DPM unit, to undertake comprehensive and internationally recognised laboratory testing, to evaluate the new design, and to undertake an underground series of tests to establish the robustness and reliability of the new approach.

The PDM gives real-time readings and is mounted within the miner's cap lamp battery and internally measures the true particle mass of aerosol collected on its filter. Measurements are insensitive to water spray as opposed optically based measurement approaches. It has been recognised that the PDM's unique measurement approach has application to allow real-time atmospheric monitoring of finer sub-micron sized particulate matter and in particular DPM found in modern mechanizer mining method atmospheres. The industry has had to date no real-time direct reading atmospheric DPM monitor. Under the project Thermo Fisher Scientific has undertaken structural changes to the PDM to convert it to a DPM real-time monitoring underground instrument, the D-PDM. The Pennsylvania Pittsburgh Research Laboratories of NIOSH (the group that originally contracted for the PDM development) has undertaken laboratory "calibration or verification" testing. A phase of Australian mine robustness and engineering testing has been undertaken to ensure the instrument can effectively assist mine management to help handle this health issue.

Tests have been undertaken at points of expected high atmospheric DPM such as during coal mine Long Wall (LW) face equipment moves and during Development Headings machine extraction. The paper discusses how the monitors have performed within the underground mine environment in evaluating DPM during the various phases of LW moves. The project has closely examined the influence of aspects of the mine ventilation system. Results have been compared to alternative industry pollutant measuring approaches and particularly those adopting the use of SKC shift length averaging monitors making use of analysis using the NIOSH developed 5040 analysis technique. The outcomes of the project demonstrate a new tool for understanding the atmosphere I mines and other confined places using diesel powered equipment n the presence of DPM.

DEVELOPMENT OF PERSONAL DUST MONITOR

A new PDM for respirable dust developed by the company Rupprecht and Patashnick (now Thermo Fisher Scientific), under a project funded by NIOSH, has generated promising results in underground coal mine testing performed in the US (Volkwein et al, 2004a and 2004b). Results from an ACARP funded study undertaken to evaluate this new realtime dust monitor for personal respirable dust evaluation particularly in engineering studies have been described by Gillies, 2005 and Gillies and Wu, 2006.

The instrument has potential to be used as an engineering tool to evaluate the effectiveness of dust control strategies. Being a personal dust monitor, the instrument measures the airborne dust from the breathing zone region and so has many advantages over instruments that measure from a fixed-point location. It can quickly highlight high dust situations and allow the situation to be corrected. The underground workplace has varying respirable dust conditions due to aspects such as ventilation conditions and air velocity, shearer activity and design, shield movement, armored face conveyor movement, manning position, face time of individual personnel, outbye conditions and dust levels in intake air and measurement instrument behavior. A study has evaluated the instrument as an engineering tool that can assess the effectiveness of a single change to improve dust levels in a sufficiently short time that other influencing aspects have not changed.

The PDM is a respirable dust sampler and a gravimetric equivalent analysis instrument that is part of a belt-worn mine cap lamp battery. The main components of the device include a cap lamp and sample inlet, a belt-mounted enclosure containing the respirable dust cyclone and a sampling and mass measurement system. There is a charging and communication module used to transmit data between the monitor and a PC while charging the monitor's lithium ion batteries. Figure 1 illustrates the unit.

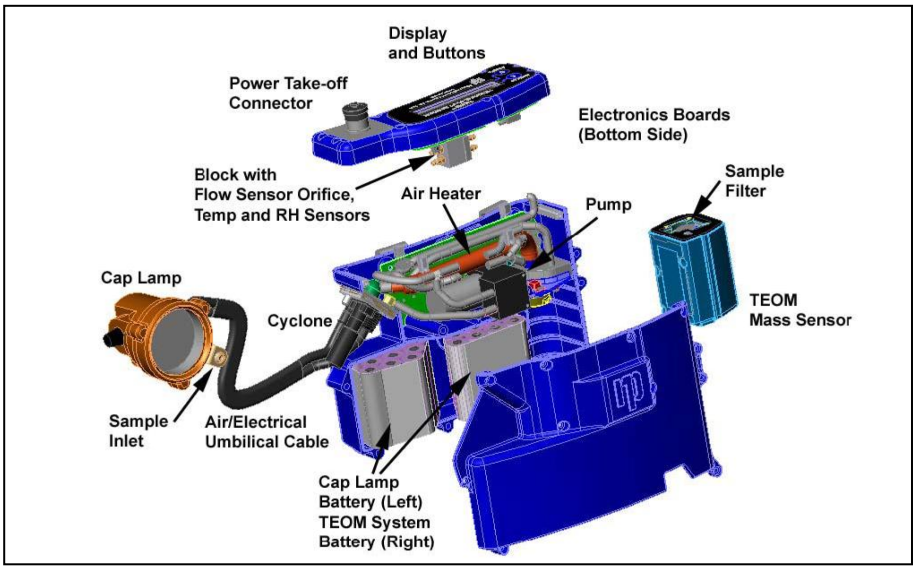


Figure 1 Major components of the PDM

The current US Federal congressional legislative program includes responses to strengthen mine emergency response plans and the Mine Safety and Health Administration's ability to investigate accidents, enforce health and safety regulations, strengthen rescue, recovery and accident investigation practices and update the 40 year old respirable dust standard that is not effectively preventing today's miners from developing black lung disease. Part of this move may require miners to be equipped with the new PDMs developed and certified by NIOSH and authorize miners to adjust their activities to avoid respirable dust overexposure.

Based on the tests conducted the PDM has demonstrated its potential use as an engineering tool to locate and assess various sources of dust during normal mining operations. The principles and concepts used to identify and fix some of the higher dust levels are generally common sense. However, to make the most effective use of this information, training and experience in using this type of technology will be very important. Experience with the data from the unit will help miners gain confidence to use the information to maintain reduced or safe dust levels during mining.

DEVELOPMENT OF THE REAL-TIME PERSONAL DIESEL PARTICULATE MONITOR

Mine atmosphere measurements of DPM in Australian mines have been measured systematically since the early 2000s. Most initial atmospheric readings have been taken on a shift average basis using SKC sampling units. The SKC is derived from a US NIOSH design and gives readings in the surrogate Total Carbon (TC) or Elemental Carbon (EC) units after laboratory analysis procedures have been completed.

- DPM = TC + inorganics = EC + organic carbon (OC) + inorganics
- TC in mine testing is generally 80% of DPM (Volkwein 2006).

Some DPM regulatory guidelines are starting to emerge in Australia and the individual states are generally moving to acknowledge DPM limits of 0.2 mg/m^3 submicron particulate matter, 0.16 mg/m^3 TC particulate and 0.1 mg/m^3 EC particulate. A few prescriptive mining regulations are in force internationally such as those applying to the US metalliferous mining industry from May 2008 based on a DPM limit of 0.16 mg/m^3 TC particulate. The real-time DPM monitor is being developed on the basis of the successful PDM unit. Thermo Fisher Scientific has undertaken structural changes to the PDM to convert it to a submicron real-time monitoring underground instrument, the D-PDM. The Pittsburgh Research Laboratories of NIOSH (the group that originally contracted for the PDM development) has undertaken laboratory evaluation of the concept. The real time DPM unit continually reports levels of mine atmosphere submicron aerosol in mg/m^3 from real-time readings.

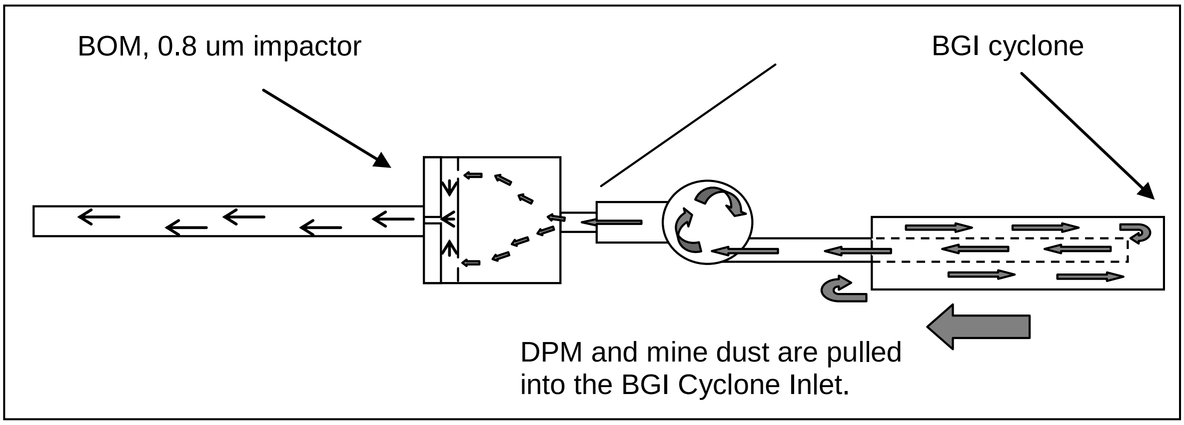


Figure 2 Schematic of prototype D-PDM Sampling Inlet.

The submicron size-selective inlet selected for this potential field instrument was the BGI 1-µm sharp-cut cyclone model SCC0.732 followed by a Bureau of Mines (BOM) designed 0.8 micrometre cut point impactor, at a flow rate of 1.7 lpm. Figure 2 shows the size selective configuration.

The D-PDM instrument is currently at a prototype stage and as with all new technologies will need industry acceptance and support to reach its full potential.

MONITORING OF DIESEL PARTICULATE MATTER

The mine tests by their very nature were restricted to equipment available for testing underground. Six of the mines visited (Mines A to F) focused on LW equipment moves from one panel to another and particularly examined the various ventilation arrangements used during shield transport to the installation roadway. The real-time DPM monitors successfully evaluated changes during the different tests and between different steps within the individual tests.

Mine A

Mine A testing found it was straight forward to analyse results for arrival and departure times of diesel machines at the face and see whether these matched the arrival of the vehicle exhaust plume. Figure 3 examines one three hour period record of real-time DPM readings as compared to heading air velocity and shield carrier speed. Close examination of results from #108 monitoring the DPM downstream of the main gate (MG) and back road showed that when the shield carriers travel in that in three cases they arrived at the tail gate (TG) end of the face in advance of the peak level of the DPM cloud. This indicated that the carriers were generally travelling at higher average speed than the air velocity. However Carrier #1112 arrived slightly later indicating slower machine travel speed than air velocity. The time difference and the peak concentration depend on the air velocity and shield carriers' travel speeds. Put simply if the shield carrier travels at the same speed as air velocity peak concentration will be extremely high and the carrier will arrive at the same time as the peak. Note that the DPM data has a lag time because it is presented as a rolling average concentration over the previous 10 minutes or 30 minutes.

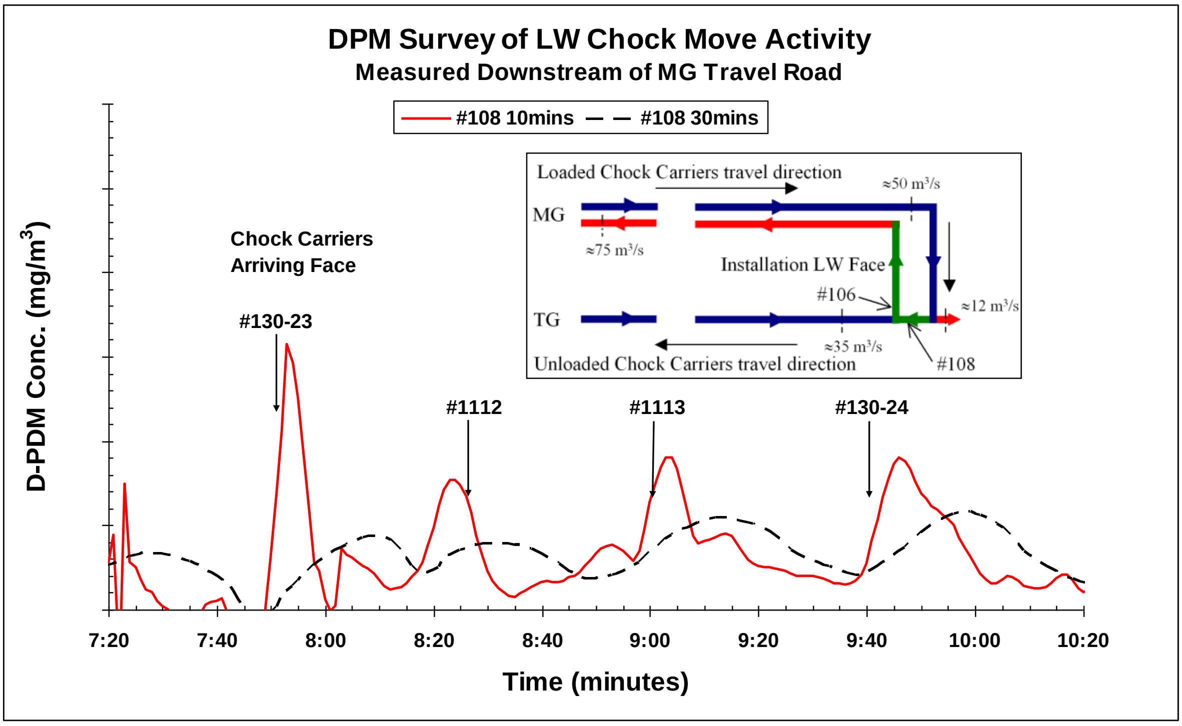


Figure 3 Observations on shield carrier DPM over a three hour period at monitor 108 fixed location.

Mine B

Mine B completed an audit on sources of DPM within a LW installation panel by strategically placing the real-time DPM monitors at points as shown in Table 1. DPM make values account for DPM monitored value in air mg/m^3) and air quantity diluting the exhaust (m^3/s). These values (mg/s) give a value that can be compared for different equipment under varying ventilation and other mine conditions.

Table 1 Sources of DPM identified in the installation LW panel in Mine B.

Location	**Sources (μg/s)**	**%**	**Comments**
MG C & D Hdgs	3.03	18.6	Mains air at MG entrance
Borehole	0.00	0.0	back of LW panel, fresh air
LW Face	4.77	29.2	Shunting Mule or LHDs
TG D Hdg	6.96	42.6	Shield carriers travel way
TG C Hdg	0.00	0.0	No diesel activity
Leakages	1.57	9.6	Mains air; coffin seal & double doors
Measured Total	**16.32**	**100.0**	

Mine C

Mine C examined one 2.5 hour period as a 37 tonne Dozer was brought in to pull the first shield on recovery a LW face as shown in Figure 4. About 51 m^3/s of air was measured on the LW recovery face. Between 14:45 and 15:32, the Dozer attempted to pull out the first shield but was unsuccessful. It worked hard much of the time at maximum revs. Between 15:32 and 16:00, a Shield Carrier Chariot was chained to the Dozer and together they successfully pulled the first Shield while working hard. A general observation on LW moves was that some high submicron aerosol readings were recorded due to the large numbers of diesel activities in working sections of the mine. This was contributed to by frequent vehicle movements or traffic jams. Miners should not be placed working inbye heavy vehicles working very hard such as the dozer when pulling shields. For the LW Move routes it is best if vehicle travels against airflow direction.

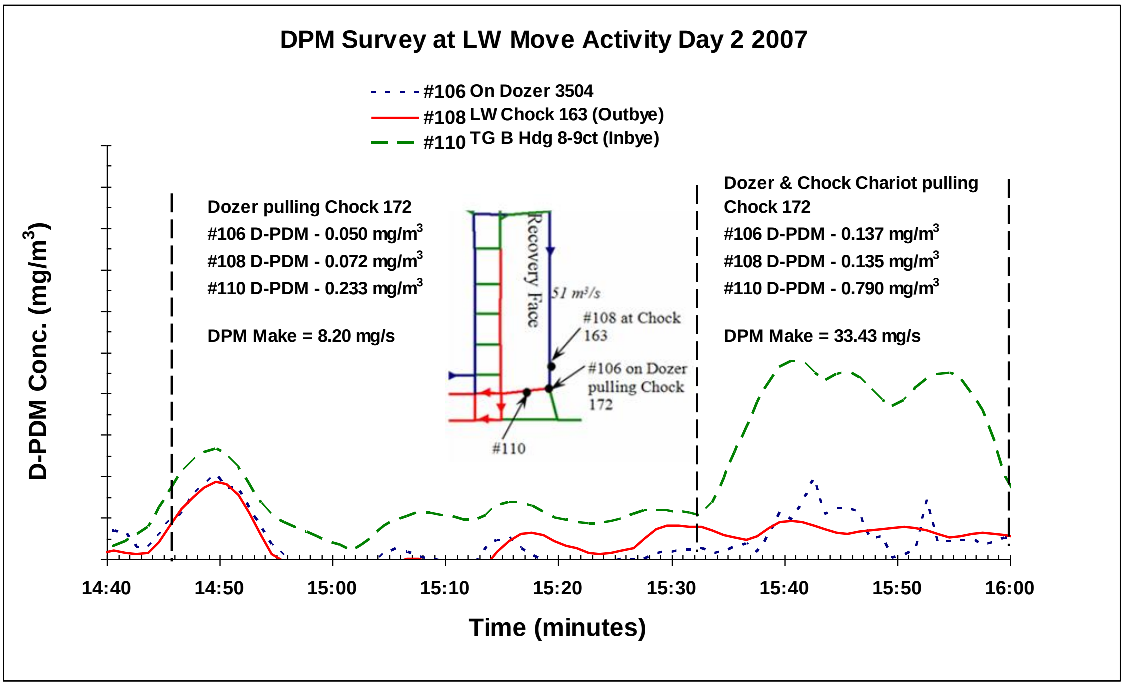
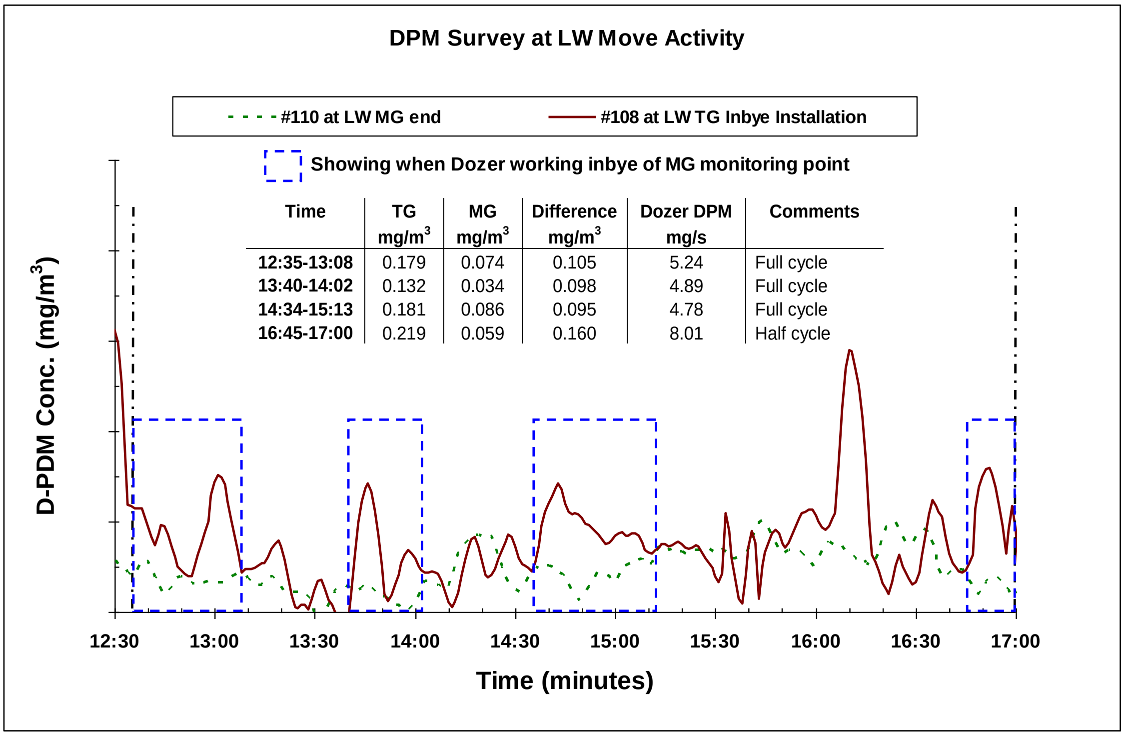


Figure 4 Submicron DPM in LW Recovery Face Pulling Shield.

Mine D

Mine D monitored a highwall mine with no underground Mains headings. Ventilation quantity was high and air entered the panel in a clean state. It was found over a number of tests that 62% of DPM within the panel was generated by Carriers hauling Shields in the gateroads and 38% generated by vehicle movement along the LW face. Air passing down the segregated belt gateroad reached the face clean and could have been used to better effect on the face where operators were installing newly arrived shields. When planning LW moves mines should evaluate and review alternatives for ventilating shield travel roads to the face. The DPM plots in Figure 5 show variability with the Dozer working as four shields were installed. The difference between LW MG and TG plots clearly shows contributions of the face Dozer.



Time	TG mg/m^3	MG mg/m^3	Difference mg/m^3	Dozer DPM mg/s	Comments
12:35-13:08	0.179	0.074	0.105	5.24	Full cycle
13:40-14:02	0.132	0.034	0.098	4.89	Full cycle
14:34-15:13	0.181	0.086	0.095	4.78	Full cycle
16:45-17:00	0.219	0.059	0.160	8.01	Half cycle

Figure 5 DPM in Mine D LW Installation Face outbye/inbye the face working dozer

Mine E

Mine E tests on the recovery face were in a well ventilated situation with clean gateroad belt heading air significantly diluting any DPM pollution from the gateroad travel heading. An electric tracked “mule” moved Shields along the face and did not add DPM pollution. Figure 6 shows influence of DPM make at the installation face with outbye monitored levels subtracted. The close match between times chariots’ face time and DPM pollution levels inbye can clearly be seen. General recommendations were in a planning a LW move it is advantageous to evaluate and review all alternatives for ventilating Shield travel roads to or from the LW recovery and installation faces to reduce peak and average miner exposures.

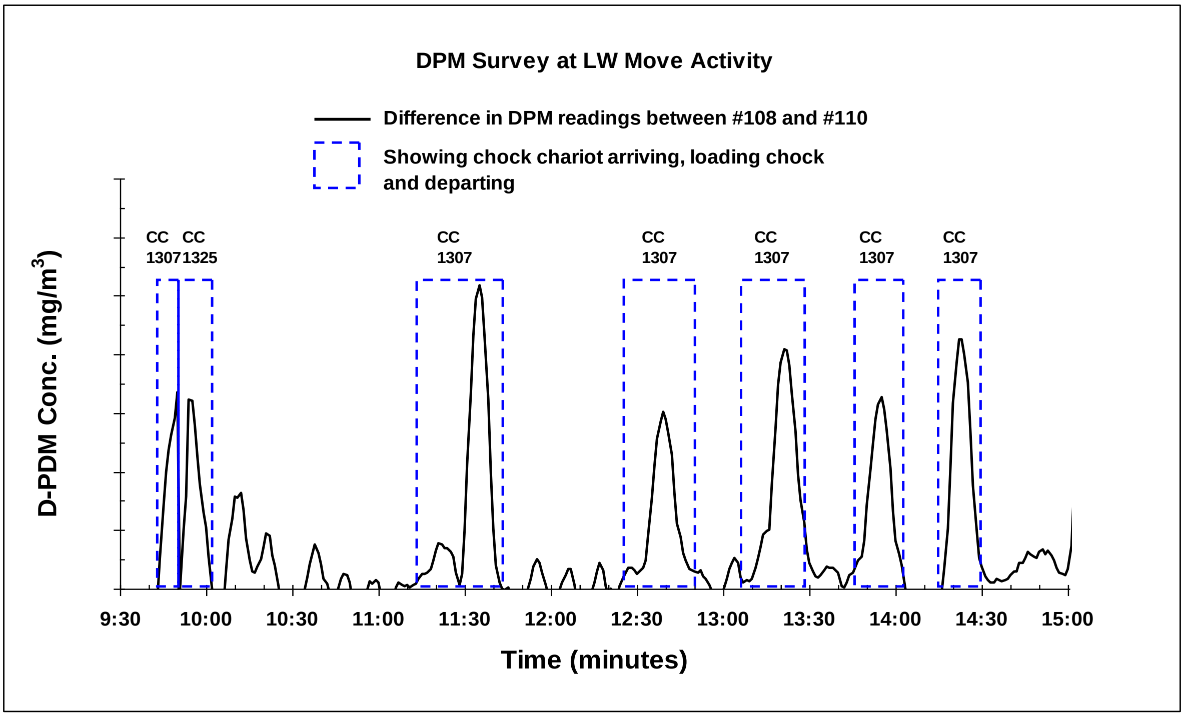


Figure 6 Difference in outbye and inbye DPM in Mine E LW Installation Face

Mine F

Figure 7 shows the influence of DPM make from diesel activities at a LW face with outbye monitored levels subtracted. The close match between time the chariots and loader were operating in the face and monitored pollution levels inbye is clearly seen.

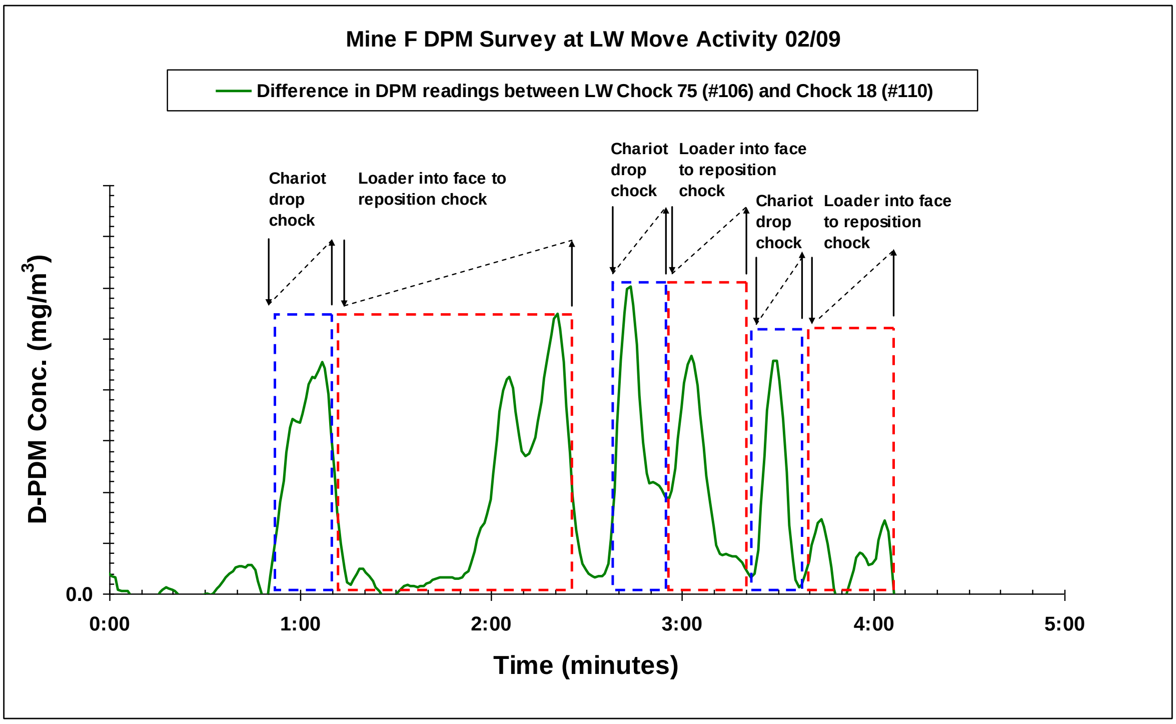


Figure 7 DPM and diesel activities in Mine F LW Installation Face

An audit was completed on sources of DPM within the LW installation panel by strategic placement of the DPM monitors. It was found that 25% was contributed from outbye diesel activities in Mains, 25% from diesel activities in panel the Travel Road, and 50% from diesel activities within face areas. A good initiative in this mine has been to limit the number of vehicles in the panel by the use of a Tag Board and Traffic controller at the panel travel road entrance. The diesel Tag Board design should consider the diesel loading from outbye Mains diesel activities which account for up to 25% of the total diesel loading for the LW panel. Summary of DPM levels from each shift at points monitored throughout the panel showed increasing levels from influence of additional equipment in series within the ventilation circuit.

SKC MINE COMPARISON TESTS

Mine SKC Test Results

It is appropriate to compare field results from the real time DPM monitor with another available measuring instrument. The only other unit available in Australia for measuring mine atmosphere DPM is the NIOSH developed SKC impactor system. The SKC system delivers shift average results and not real time results. The SKC system results are analysed by the laboratory NIOSH 5040 method.

During mine investigations parallel underground SKC samples have been taken for comparison with the mine real time DPM monitored results. Under the SKC system the sample is drawn first through a respirable cyclone sampler for organic carbon (OC) associated with the absorbed organic substances and elemental carbon (EC) from the soot cores themselves.

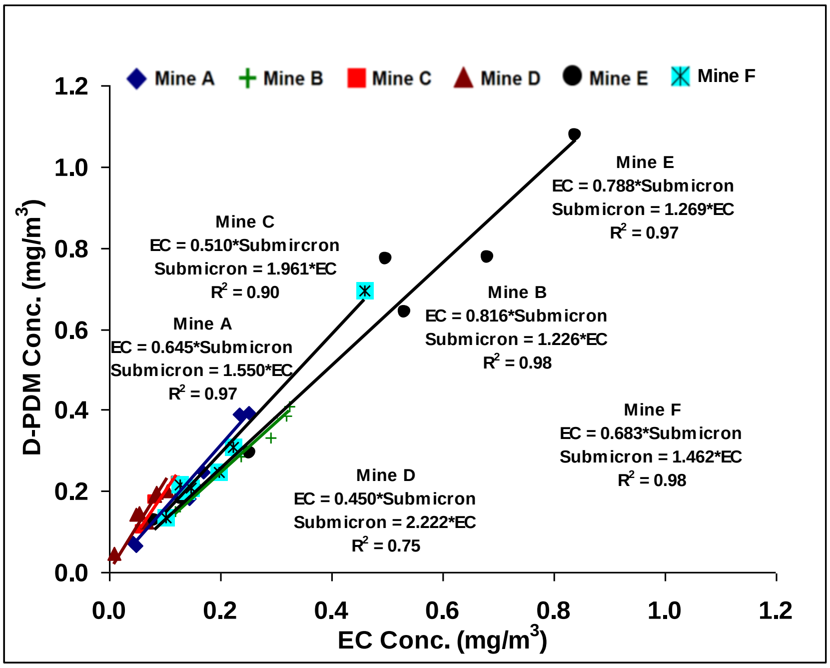


Figure 8 Mine individual relationships between EC and Submicron DPM

TC is the sum of the OC and EC. TC according to Volkwein (2006) makes up consistently over 80 percent of the submicron DPM material that passes through the impactor in the SKC system. From various research and studies conducted so far, TC has been measured at over 80 percent of submicron DPM sample mass. Dabill (2005) states that comprehensive research has shown that over 95 percent of diesel particulate has an aerodynamic diameter of less than 1 µm, whereas virtually all coal dust has particles larger than 1 µm. Consequently by collecting the submicron fraction the coal dust is effectively eliminated.

For comparison purposes of a related set of Longwall move results Figures 8 and 9 show Mines A to F D-PDM results compared with SKC impactor determinations of EC and TC particulate shift average results taken in the particular mine at the same time. Close correlations were found for all cases ($R^2 \geq 0.98$) for TC versus D-PDM. All EC versus D-PDM correlations were good ($R^2 \geq 0.90$) except for one set of mine results. The results demonstrate that calibration relationships (the slopes of the individual mine relationships) vary between mines. This differences in suspected to be due to variations mine to mine in aspects such as mine atmospheric contamination, vehicle fleet variations, fuel type, engine maintenance, engine combustion efficiency and engine behaviour.

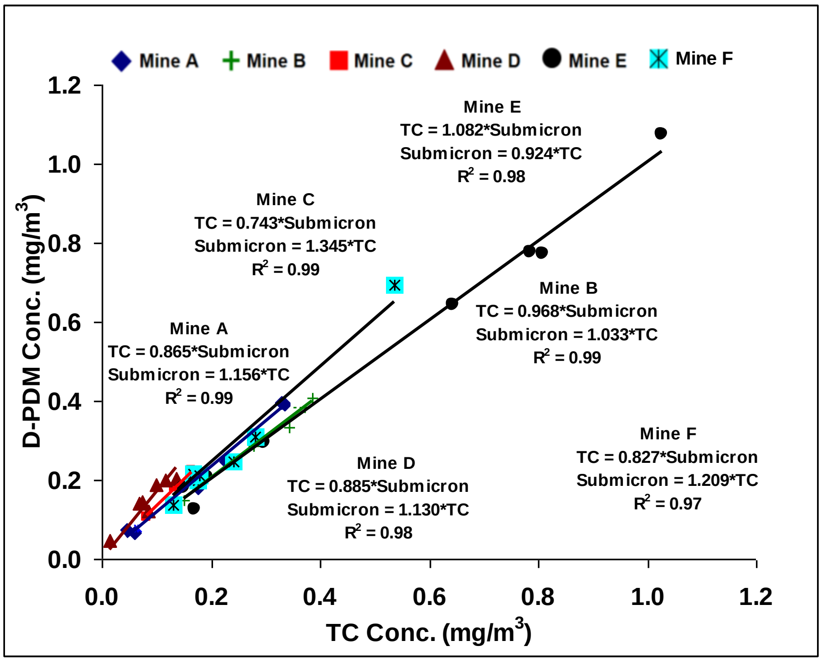


Figure 9 Mine individual relationships between TC and Submicron DPM

Figure 10 shows combined results from the all mine test series compared with SKC impactor collection determinations of EC and TC particulate shift average results taken in the particular mine at the same time. The combined mines calibration relationships are close with R^2 = 0.95 for TC compared with submicron D-PDM and R^2 = 0.95 for EC compared with submicron D-PDM.

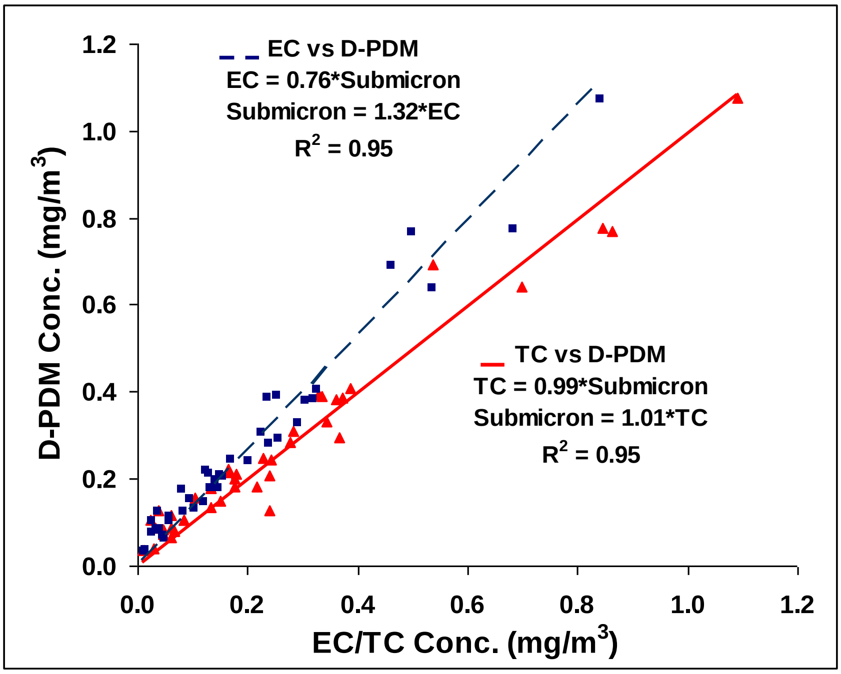


Figure 10 Combined relationships for Six mines between EC or TC and Submicron DPM.

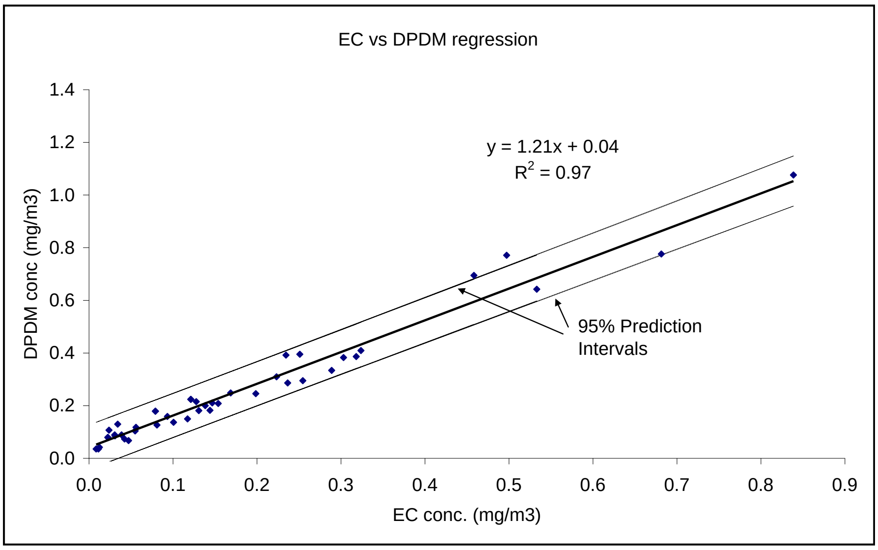


Figure 11 Combined relationships for Six mines between EC and Submicron DPM.

Figure 11 shows combined DPM results from the all mine test series compared with SKC impactor collection determinations of EC particulate shift average results taken in the particular mine at the same time. The distribution shows the calculated upper and lower 95% confidence limits about the regression. The combined mines relationships are close with R^2 = 0.97 for EC compared with submicron DPM.

There is some international debate on the DPM monitoring issue of whether submicron DP, TC or EC should be evaluated. The D-PDM is the only real time instrument available to measures submicron DP. Various international studies show that in the normal mine atmosphere (with moderate loadings of respirable dust below statutory limits) the differences and the potential levels of error between the three approaches in monitoring DPM are relatively minor (Birch and Cary, 1996, Birch and Noll, 2004 and Dabill, 2005).

Comparison between D-PDM and SKC Monitoring

A comparison between D-PDM and SKC monitoring systems has been drawn and indicates the following. The D-PDM monitoring system has the following comparative advantages and disadvantages.

- D-PDM gives real time results that can be used to assess whether an atmosphere is safe for work immediately.
- D-PDM gives immediately available results that can be used to improve the mine system and work practices.
- Mine atmosphere results can be compared directly with Workshop engine monitored results.
- D-PDM can be used for both real time analysis of situation and shift duration comparison.
- Total Costs (capital cost and operating costs) for D-PDM analysis are likely to be less over a period than for SKC analyses as no laboratory analyses needed.
- D-PDM based on all submicron particulate (TC plus other mineral matter).
- D-PDM results at low levels may be influenced by coal dust interference but this error is less than 5 percent according to Dabill, 2005.
- D-PDM results may also be influenced by some other particulates such as smoking and welding fumes (not an issue in coal mines).

On the other hand the SKC approach has been in use since the mid 1990's while the D-PDM approach is a more recent development. A summary comparing SKC and D-PDM approaches shows:

- SKC gives shift duration results that are designed to be used for regulatory purposes and to retrospectively assess whether an atmosphere was safe to work in.
- SKC results are awkward for use in engineering evaluation and improvement exercises in complex mine atmosphere and working places.
- Mine atmosphere results can be compared directly with workshop engine monitored results.
- Total Costs (capital cost and operating costs) for SKC analysis are likely to be greater than for D-PDM as expensive lab analyses needed.
- SKC gives a surrogate estimation of atmosphere submicron particulates DP based only on TC and EC and does not include other mineral matter.
- Relationship between TC/EC and DP varies mine to mine.
- SKC results are likely to be more accurate if vehicles are working in dusty return air.
- SKC results may be influenced by some other particulates such as smoking and welding fumes (not an issue in coal mines).

PARALLEL REAL TIME RESPIRABLE DUST AND DPM SURVEYS ON VARIOUS MINE SECTIONS AND ACTIVITIES

A number of studies have been undertaken in which PDM units and D-PDM monitors have been used to record mine atmosphere particulate matter over an extended period of a shift. Figure 12 shows monitored results with one PDM (#134) and one D-PDM (#106) side by side at a point in underground intake air in which diesel engine vehicles are operating. The trend lines move together over time and show that the diesel particulate mater level is generally 50 to 70 percent of the respirable dust level through out the shift.

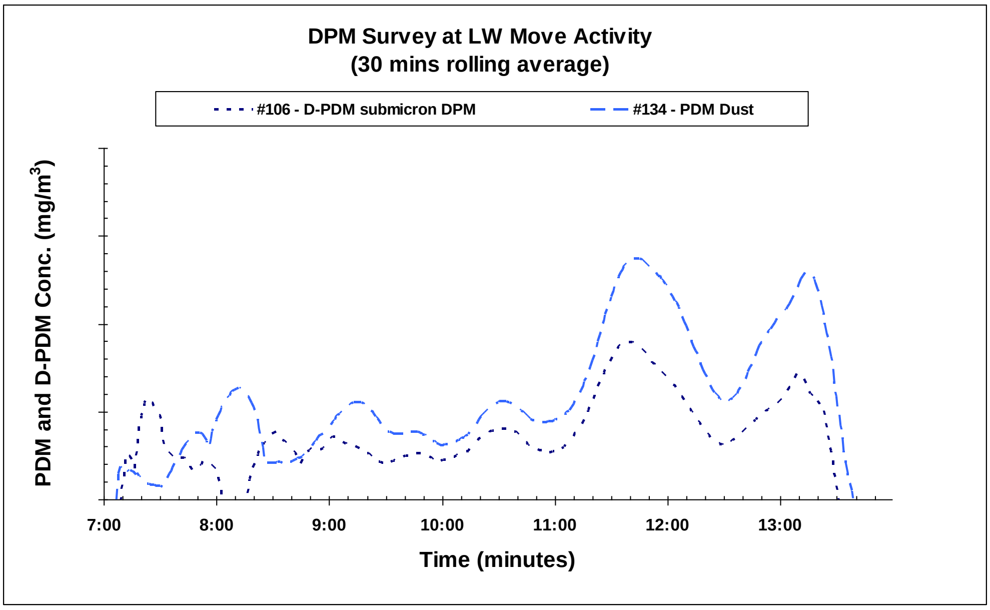


Figure 12 Monitored results with one PDM (#134) and one D-PDM (#106) side by side at a point in underground intake air in which diesel engine vehicles are operating

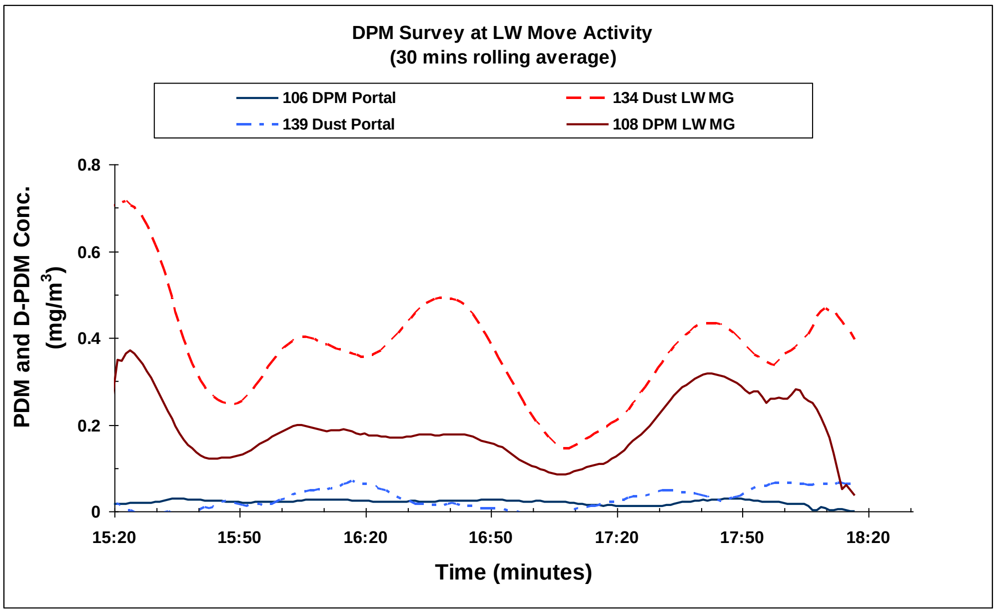


Figure 13 Monitored results with PDM (#139) and D-PDM (#106) and PDM (#134) and D-PDM (#108) side by side (upper trend lines).

There was no actual coal production involved in any of the activities monitored. All PDM respirable dust readings taken (ranging from 0.18 - 0.76 mg/m^3) were well below the regulatory limits for respirable dust.

Figure 13 shows monitored results undertaken at another mine with two PDMs and two D-PDMs in use simultaneously. PDM (#139) and D-PDM (#106) were side by side (lower trend lines) and were at a surface portal while PDM (#134) and D-PDM (#108) were side by side (upper trend lines) in intake air just outbye a longwall face during installation of shields. Conclusions that can be drawn are:

- Portal air records little DPM or respirable dust. Minor variations were due to vehicles waiting in a line and dust from equipment movement.
- The trend lines for the monitoring position just outbye the face move together over time and show that the diesel particulate mater level is generally 50 to 70 percent of the respirable dust level through out the shift.
- There was no actual coal production involved in any of the activities monitored. All PDM respirable dust readings taken were well below the regulatory limits for respirable dust.
- Significant DPM and respirable dust are added to the intake air as the ventilation moves towards the panel face. At times these are above what may be considered as “target levels”.

CONCLUSIONS

A project on diesel particulate matter real time monitoring development supported by ACARP grants in recent years has been discussed. The project received substantial NIOSH support and is an example of practical application that has received considerable additional industry financial support, mine site testing and evaluation assistance. The outcome is that the objective testing over a number of different approaches and the comparisons with the SKC monitoring approach lead to the conclusion that the D-PDM is accurate when compared to existing measurements from the SKC method. The principal industrial application of the D-PDM will be to give a greater understanding of DPM levels in mine environments in regulatory, statutory and engineering evaluation exercises. The underground tests have given examples of many applications of the D-PDM for future industry use. Some design issues to make the unit more robust and with a permanent inlet classification system are under examination. New industry applications of the D-PDM that may be successfully implemented in the future warrant attention.

The paper has discussed how the monitor has performed within the underground mine environment in evaluations of the various phases of longwall structure moves. It has closely examined the influence of aspects of the mine ventilation system. The monitor is demonstrating the potential to improve understanding of the mine environment and to empower and educate operators in the control of their environment.

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The project would not have been possible without the guidance, support and contributions of the US agency NIOSH. NIOSH undertook laboratory evaluations, contributed to the design of the D-PDM and gave general assistance and advice throughout. Particular thanks are given for the efforts of Mr Jon Volkwein, Senior Scientist with NIOSH. Jon travelled to Australia with another NIOSH scientist, Dr Jim Noll, during the project and gave support in a number of areas including underground testing and technology transfer seminars. The personal enthusiasm and commitment of Mr Erich Rupprecht, formerly CEO of Rupprecht and Patashnick Corporation and Mr Jim Morton of Thermo Fisher Scientific was essential to the success of the projects. The assistance of these gentlemen and their professional work colleagues is acknowledged.

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