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- An analysis of airflow patterns around a longwall shearer with a proposed modified spray system for dust control
- An evaluation of fuels and retrofit diesel particulate filters to reduce diesel particulate matter emissions in an underground mine
- XLP/ULP On-Reef Mechanised Mining Method by Ventilation on Demand as a Concept

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Photo taken by Louis Nel. Refrigeration plant for deep platinum mining

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CSIR Property Cnr Rustenburg and Carlow Road
Emmarentia
P O Box 291521 Melville 2109
Tel: +27 11 482-7957
Fax: +27 11 482-7959 / 086 660 7171
E-mail: secretary@mvssa.co.za
info@mvssa.co.za
Website: http://www.mvssa.co.za

Advertising and Production:
Delinds Publications
12 Delta Road Blairgowrie Randburg
PO Box 72366 Parkview 2122
Tel: +27 11 886-5985
Fax: +27 11 886-1332
Cell No: +27 83 266 6662
E-mail: delinds@mweb.co.za
Advertising: Debbie Myer
Production: Lindsay Myer

Editor's Comment

Where to in 2017

Prof Jan du Plessis
Honorary Editor

Please send your comments and opinions to info@mvssa.co.za

As the year 2016 draws to a close, many of us will reflect on what can only be described as one of the toughest years that the mining industry has had to face since the middle to late 1990s.

Continuous changes to the legislative framework around the globe have seen many mining houses re-positioning themselves in anticipation of the next growth areas within the commodity sectors.

Recent changes in the international political arena have seen gold lose its shine as prices drop. However, higher user commodity prices increased in the anticipation of stronger growth in the global markets as anticipated for 2017.

We are all principally employed within the mining industry where operational as well as capital resources have been severely curtailed over the recent past. This includes the continued increases in energy costs, specifically electrical input costs, where ventilation and cooling remains one of the biggest energy consumers within our mines.

In this issue of the journal a review of the potential impact of ventilation on demand (VoD) is given. This study confirms that the future of mine ventilation will have to change drastically from a 24 /7 continued airflow delivery, to delivery when and where needed.

The continued focus on worker health issues together with the court findings against mining houses and in support of the silicosis class action case, reiterates the importance of developing engineering solutions to support the delivery of clean and healthy air in underground operations. Two papers in this journal deal with this subject. The first paper analyses dust control on a coal longwall operation and the second paper evaluates the reduction in diesel emissions.

In 2017 it is hoped that the global economic growth will improve, therefore increasing the demand for commodities and so improving the financial conditions in which mines operate. Given this we will need to continue our focus on redesigning mines and the equipment used to improve the overall conditions - but this will all have to be done more cost effectively.

The role of the mine ventilation and occupational hygiene engineer remains pivotal in assisting mining engineers to achieve these goals.

The development of technology and the research to support this must be undertaken. The key will be not only the development, but also the rate in deployment of new technology.

In the South African context, the establishment of the Mining Precinct is a very positive step because research into engineering solutions have been left to industry and industry partners, with all incremental developments associated with direct research funding from Mining Houses.

The objective of this initiative is to foster collaborative research amongst all research organisations, research centers, institutes and universities. Key focus areas will be the automation and modernisation of the mining industry as well as the different ventilation, cooling and potential hygiene impacts which will have to be considered into the re-engineering required to meet future mining needs.

It is therefore clear that many new challenges lie ahead of us in 2017, and we can look forward to another exciting year.

May you all have a blessed 2017.

MVS Public Relations Committee - Communication Facility

The MVS Public Relations Committee would appreciate any feedback on any matter relating to the operation of this society. This facility has been initiated in order to ensure that any matter that is raised is given due attention.

It would be appreciated that the questionnaire below be completed and faxed or e-mailed to any one of the person/s listed below:·

- Prof Jan du Plessis info@mvssa.co.za, or
- MVS Office, Fax 086 660 7171, e-mail secretary@mvssa.co.za

All communications will remain confidential in terms of identification of the communicator. Should you wish to remain anonymous you are welcome to do so.

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CSIR Property, Cnr Rustenburg and Carlow Road, Emmarentia
P O Box 291521 Melville 2109
Tel: +27 11 482-7957
Fax: +27 11 482-7959 / 086 660 7171
E-mail: secretary@mvssa.co.za
info@mvssa.co.za
Website: http://www.mvssa.co.za

President's Christmas message

As I write this, I notice that it is precisely 3000 days since the defining starting point of the Great Recession, the collapse of Lehman Brothers. Before that day, the world economy was roaring, with mining commodities and the mining industry leading the way. During the intervening years, many of us in the industry have been touched by retrenchments, shaft closures, and industry malaise.

Fortunately, during these past years, the owners and managers of the more progressive mining companies have come to the realisation that their most valuable assets are their employees, and that ensuring their safety and health results in increased productivity, allowing them to produce more with less (and fewer). While challenges remain with regard to silicosis and hearing loss, the fatality rates have dropped to levels that most of us who have been in the industry for some time would have imagined to be impossible 25 or 30 years ago.

The unique skills of members of our discipline are in high demand. South African trained mine ventilation professionals are employed at operations around the globe, and if I may judge by recent experiences, it's about time. Our knowledge of the fundamentals of mine ventilation, as well as the continuous collaboration and interaction that exists between our members, stand us in good stead to be able to address any challenge that may arise. The training manuals, textbooks, and other material produced by the MVSSA are recognised as world-class.

The mining industry is usually the first to fall and the last to recover from economic shocks, but there are positive signs - major world economies are recovering, implying an eventual return to cyclical upswings in mining. Good quality mining people are in huge demand - recently for the first time ever, the most highly paid new graduates in the USA are mining engineers, surpassing even those from the Harvard Law School.

I look forward to the coming upswing, when mining companies will be able to do more with more, especially combined with the vastly improved baseline that has been established in safety and health.

The Mine Ventilation Society of South Africa has been a beneficiary of the beginning of the new positive cycle. Membership is growing, our annual conference was extremely well-supported, and our financial position is strong. The transfer of our discipline qualifications from the Chamber of Mines is making very visible progress, with final curricula being signed off. I would like to express my congratulations to the Education committee for achieving these milestones after a number of years of difficult negotiations.

Our recent focus on improving the quantity and quality of communication to members and supporters is beginning to bear fruit. Our relaunched website is growing in traffic, and our membership database is more complete than it has been in many years. I would like to encourage our members to share with the Society those 'tips and tricks' that help us do our job on a daily basis.

Improved accessibility to knowledge will benefit everyone in our discipline - rather than spending time discussing the basics of mine ventilation, I envisage a Society and discipline where all practitioners understand and agree on the basic premises. The 'real work' can then proceed much more smoothly - that of designing improved ventilation systems that benefit all of those who work in the challenging environment of underground mining and its associated fields.

On behalf of the Council, I wish to express our condolence to the families, friends, and colleagues of members who have passed away during 2016. A number of our long-time colleagues have also announced their well-deserved retirement.

I wish to thank all the members of the MVSSA and Council as well as all of our sponsors and supporters for their invaluable contributions during the year.

Finally, I wish all members of the MVSSA and their families a safe, healthy, and joyous festive season. May you enjoy this time of year when we express our commitment to loved ones. May 2017 be filled with joy and prosperity for all.

Peer reviewed for Journal publication

An analysis of airflow patterns around a longwall shearer with a proposed modified spray system for dust control

Y.P. Chugh, A. Chandna, H. Gurley, Mining and Mineral Resources Engineering, Southern Illinois University Carbondale

ABSTRACT

This paper presents CFD analysis of a proposed spray system with several modifications made to the chassis, ranging arm and shearer-clearer sprays. Modelling and dust dispersion studies reveal that the system should be much better at controlling dust control in the walkway region than the current sprays and engineering controls. Interaction among sprays in different areas is minimised, and multiple shearer-clearer arms and spatial location of proposed sprays design minimise the dust travelling toward the walkway. The designed venturi effect created with operating sprays over the shearer chassis should further reduce mine workers' risk of exposure to coal dust.

INTRODUCTION

National Institute for Occupational Safety and Health (NIOSH, 1995) data shows that more than 76,000 miner deaths since 1968 were related to coal workers' pneumoconiosis (also known as black lung or CWP). Coal mine dust and silica have been identified as the major causes of this disease (NIOSH, 1995).

Besides CWP, coal dust can also be responsible for many other medical conditions such as non-malignant respiratory disease (NMRD) and interstitial and obstructive pulmonary diseases (NIOSH, 1995). These diseases have no known cure and may be fatal in the long term. Therefore, the Mine Safety and Health Administration (MSHA) has imposed more stringent dust control regulations to protect coal miners from the harmful health effects of coal dust. MSHA implemented the Final Rule on August 1, 2014 (MSHA, 2014) with new dust regulations scheduled to go into effect in 2016, which will reduce the overall dust standard from 2.0 to 1.5 mg/m^3 of air volume. In entries used to ventilate places where miners work, and for Part 90 miners (those who have evidence of pneumoconiosis), the exposure standard would be lowered from 1.0 to 0.5 mg/m^3 of air volume.

It is well known that dust control on longwall faces is much more difficult than in room-and-pillar mining, with most of the dust related to shearer, shield, and stage loaders. However, specific data on non- compliance of dust standards on longwall faces is currently not available. Longwall faces in the USA have methane content varying from 4 to 16 m^3/mt (Diamond, 1994).

Therefore, this research aims to develop improved engineering controls for dust in the longwall face area and demonstrate their expected effectiveness through the use of computational fluid dynamics (CFD) modelling.

Since fine respirable particles (<10 microns) tend to follow the path of the airflow (Ren et al., 2012; Md. Azmi, 2014), a good knowledge of these patterns around a longwall shearer is essential to develop alternate improved engineering controls.

AUTHORS' HYPOTHESES AND RESEARCH GOALS

Authors developed the following concepts for improving sprays systems design for longwall shearers:

1. Generated dust during mining must be kept as close to the freshly mined face as possible while travelling out by.
2. Air pressure distribution around the shearer should minimise dust travelling from the shearer toward the walkway and dust recirculation.
3. Attempts should be made to maintain a higher positive pressure in the walkway than the air pressure travelling out by of the shearer toward return.
4. Alternate designs should attempt to increase contact time (the time of interaction) between dust particles and water.
5. Interaction between sprays should be minimised to reduce air recirculation patterns.

Due to shearer operation and improper location of water sprays, dust-laden air can recirculate towards walkways. This can be minimised by creating spatial hydraulic curtains between the walkway and sources of dust recirculation. The hydraulic curtains maintain a positive pressure in the walkway that does not allow dust-laden air to penetrate into the walkway. The interaction time between water droplets and dust-laden air can be increased by creating air locks using hydraulic curtains that contain the dust-laden air and do not allow it to escape into an open and free-flow environment. The principal author used this concept to contain dust-laden air into the loading pan of a continuous miner (CM) with water sprays. Similarly, the principal author used hydraulic curtains on a CM behind the chassis sprays to contain the dust-laden air near the face and increase contact time between the water droplets and dust particles. The increased contact time can be estimated using CFD modelling of dispersed dust particles. With the above foundations, alternate shearer-clearer designs, spatial distribution of sprays, and geometric designs for spray blocks were conceived and tested as reported in a companion paper (Chandna, 2015).

The overall goal of the research was to analyse the dust control performance of an alternate proposed spray system around a long-wall shearer and compare its performance with the currently employed spray system (Chandna, 2015). CFD modelling was used for above assessments. A secondary objective was to highlight changes in airflow patterns and dust dispersion tracks around a longwall shearer due to implementation of the proposed spray system.

CFD MODELLING OF A TYPICAL CHASSIS SPRAY BLOCK

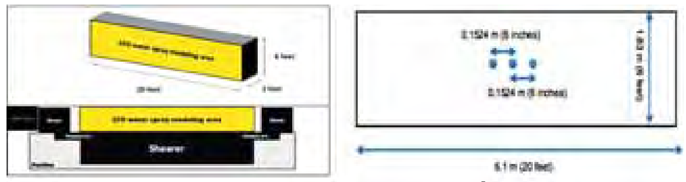
Chassis sprays on a longwall shearer are an integral part of the dust control system on a longwall face. These are mounted on the side face of the front part of the chassis and are directed at different angles at the freshly cut coalface to wet the airborne dust and make it drop out of the air. The objective of this task was to maximise the spray area covered and minimise interaction among different sprays. A typical chassis spray block box of length = 6.1 m, width = 0.91 m, and height = 1.83 m was constructed and meshed using Workbench 13.0. This box (Figure 1(a)) was designed to simulate chassis sprays that spray the longwall face about 0.91 m away. Sprays were mounted on one wall and the spray pattern was observed on the other wall along the width of the box (i.e., 0.91 m apart).

The overall design geometry of a typical 3-spray block used is shown in Figure 1(b) (Figure not to scale). The sprays were modelled to make a 0^{O} angle with respect to the horizontal as well as the vertical. To get a better idea of the coverage achieved and interaction between sprays without the influence of other external factors, this model was run with negligible airflow (i.e. the continuous phase). For simulating sprays, the discrete phase modelling (DPM) feature of ANSYS FLUENT 14.5 was utilised. BD3-2 hollow cone spray configuration was used to model these sprays (Spraying System Co.). A pressure swirl atomiser was used as the injection type, which accelerates the liquid through the nozzle swirl ports into a central swirl chamber thereby pushing the liquid against the walls of the swirl chamber and developing a hollow cone pattern. Some important general specifications of sprays used for modelling were:

1. Injection type: Pressure-swirl-atomiser.
2. Flow rate: 2.27 L/m.
3. Injector inner diameter: 0.0019304 m.
4. Spray half angle: 39^{o}.
5. Upstream pressure: 0.62 MPa. All of these are water-only sprays.

Solution convergence was achieved with an accuracy of 10^{-3} using a realisable k-ε turbulence model with standard wall functions and second order upwind discretisation for all variables with SIMPLEC for pressure-velocity coupling. The discrete phase - in this case spray droplets - was modelled with escape boundary conditions; i.e., they were terminated from calculation as soon as they hit the target wall. The following assumptions were used for all models:

1. Steady state conditions.
2. Uniform and single component (normal) inlet velocity.
3. No slip and shear conditions to roof, floor, and side walls.
4. No temperature gradient.
5. Incompressible flow.
6. Spray particles are spherical.
7. No particle-particle coalescence.



a b

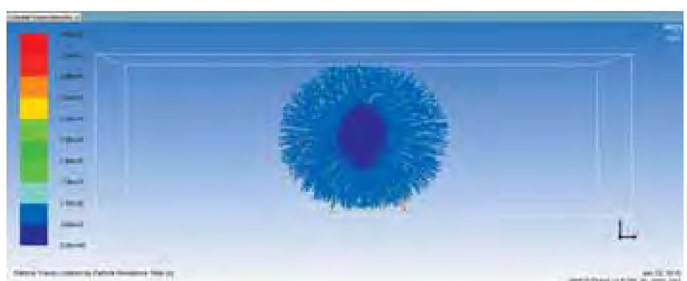
Figure 1. *Design geometry of: (a) a typical chassis spray block and (b) three sprays arranged 0.15 m apart (not drawn to scale)in a typical chassis spray block*

ANALYSIS RESULTS OF A TYPICAL SINGLE BLOCK CHASSIS SPRAY SYSTEM

Currently used design: The spray patterns are depicted in Figures 2 (a, b). The results show that:

1. The width of the wall covered along the widest distance of the spray coverage is approximately. 1.91 m, and the height covered is around 1.61 m.
2. The width of coverage from one spray was about 1.57 m that would result in theoretical width of coverage for three sprays 0.15 m apart from each other to be about 1.88 m, which is approximately what was observed experimentally.
3. There is significant interaction among the individual sprays, which impacted their area of coverage and is discussed in the next section.

(a)



(b)

Figure 2. *(a) 3-D view and (b) front view of spray pattern in a typical chassis block (Grid: Particle residence time)*

Alternate modified spray system: Based on above analysis, a modified staggered spray system was designed as shown in Figure 3 to increase the spray face coverage area. Two models were constructed based on the location of the top spray. For Model 1, all the 3 sprays were BD3-2 sprays while for Model 2 the top spray was BDW3-5 (described later) and the remaining two were BD3-2. The spatial orientation of sprays is given in Table 1. The results of simulations of the modified spray system (Model 1) are shown in Figures 4 (a) and 4 (b).

Table 1. Spatial orientation of modified sprays

Model No.	Model 1	Model 2
Distance between bottom sprays	0.41 m	0.41 m
Distance of top spray from bottom spray	0.30 m	0.30 m
Angle of sprays with respect to horizontal	0	0
Angle of sprays with respect to vertical	0	0
Cone angle (°)	78	101

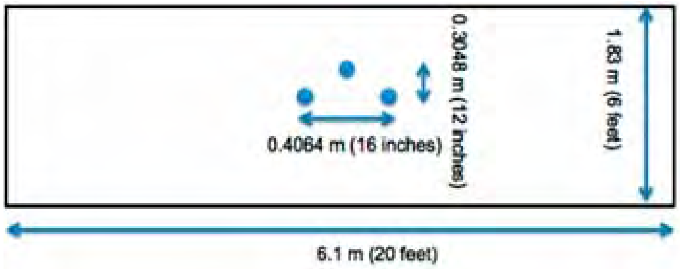
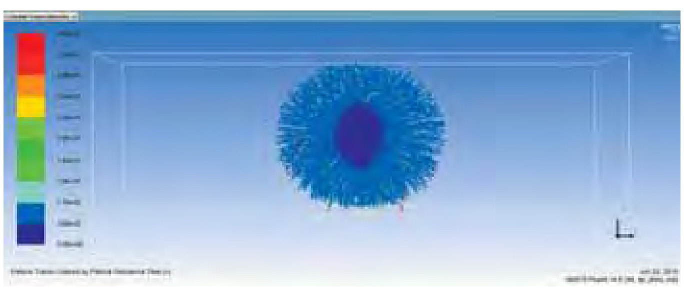


Figure 3. *Geometry of modified sprays in the designed spray block (Figure not drawn to scale)*

(a)



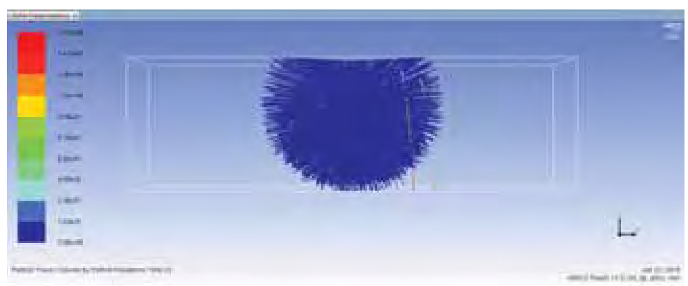
(b)

Figure 4*. (a) 3-D view and (b) front view, of a modified chassis block spray pattern and coverage (Model 1) (Grid: Particle residence time)*

Staggered spray configuration 2 (Model 2) involved replacing the top BD3-2 spray of Model 1 by a BDW3-5 spray. The BDW3-5 spray has a nozzle diameter of 0.003175 m compared to the nozzle diameter of 0.00198 m for a BD3-2 spray and operates at 4.14 Lpm flow rate at 0.62 MPa pressure with a cone angle of around 101 deg. (Spraying System Co.). The results are shown in Figures 5 (a) and (b) and discussed below.

1. For Model 1 the coverage was around 2.0 m as compared to the theoretical width of 1.88 m, which is larger than the increase observed for a typical chassis spray block. This observation led to the conclusion that two sprays placed 0.30 m apart cause each other to move outwards due to the interaction between them, but when a middle spray is placed in between them as in the case of typical chassis block, it tends to push the side sprays inwards.
2. The coverage for Model 2 was about 2.4 m along the widest distance between the particle tracks when using the 100^{e} spray at the top.
3. The general particle residence time for Model 2 ranged 0.05 to 0.1 sec as compared to 0.041 to 0.0819 sec for Model 1 due to the larger cone angle used in Model 2. This should result in more coal dust wetting time for the Model 2 spray system. However, there is more spray water volume in Model 2 due to higher volume BDW3-5 spray.
4. The proposed staggered configuration of sprays provides a much better coverage than all sprays located along a straight line. With top spray cone angle of 100 deg., the coverage is even better but at the cost of slightly more spray water volume. To maintain a pressure of 0.62 MPa, BDW3-5 uses 1.03 gpm of water as compared to 0.6 gpm used by BD3-2 spray.

(a)



(b)

Figure 5. *(a) 3-D view and (b) front view, of a modified chassis block spray pattern and coverage (Model 2) (Grid: Particle residence time)*

ANALYSIS OF THE PROPOSED SPRAY SYSTEM

A CFD analysis of the current spray system around a shearer (Chandna, 2015) revealed its several shortcomings. This was done on a longwall model having an airflow of 2.54 m/s and height and width equal to 1.98 m and 5.49 m respectively. These included;

1. Dust tends to enter walkway from the longwall face through a low velocity recirculation (RC) zone existing just above the chassis of the shearer due to a vacuum created in that region, and
2. Observations on the simulation of currently practiced spray system indicate that several improvements are needed to further reduce the respirable dust from travelling from the point of generation into the walkway.

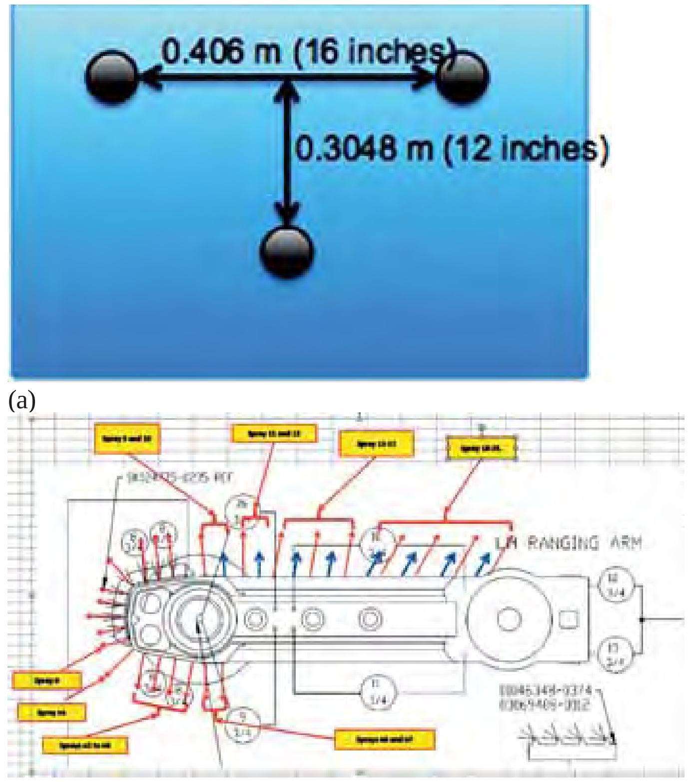
To minimise the development of RC zones in the vicinity of operators that can expose workers to dust aerosol, several changes were made to the current spray design, including number of sprays and their spatial distribution and their orientations including the use of the designed improved chassis spray block. These are described below.

Chassis Sprays: Four (4) spray blocks of the modified chassis sprays - placed at locations similar to the current system - were modelled. However, in this case they were modelled in a triangular geometric configuration with two sprays placed at the edge of the chassis around 0.41 m apart and the third spray was placed in the centre of the two sprays 0.30 m below the line containing the two sprays (Figure 6(a)). The top two sprays were oriented horizontally to spray directly onto the coalface and the bottom spray was inclined 10^{o} upwards from the horizontal plane.

Ranging Arm Sprays: Sprays 1-8 (Figure 6(b)) were modelled similar to the current system. In addition, there were other sprays placed on the ranging arm as shown in Figure 6(b).

1. Sprays 9 and 10 were modelled 0.1 m apart, 8^{o} from the vertical plane perpendicular to the ranging arm with Spray 9 (red) being 60^{o} upwards from the horizontal plane and Spray 10 (blue) being 20^{o} upwards from the horizontal plane.
2. Sprays 11 and 12 were modelled 0.1 m apart, parallel to the vertical plane that is perpendicular to the ranging arm with Spray 11 (red) inclined 60^{o} upwards from the horizontal plane and Spray 12 (blue) inclined 20^{o} upwards from the horizontal plane.
3. Sprays 13 to 17 were modelled 0.1 m apart. They were inclined 10^{o} with respect to the vertical plane that is perpendicular to the ranging arm on the negative side towards the tailgate. The sprays marked red were inclined 60^{o} upwards from the horizontal plane and sprays marked blue are inclined 20^{o} upwards from the horizontal plane.
4. Sprays 18 to 25 were modelled 0.1 m apart. They were inclined 30^{o} with respect to the vertical plane that is perpendicular to the ranging arm on the negative side towards the tailgate. The sprays marked red were inclined 60^{o} upwards from the horizontal plane and sprays marked blue were inclined 20^{o} upwards from the horizontal plane.
5. Spray 0 was placed 0.1 m below Spray 1 and had the same orientation as Spray 1.
6. Spray n1 was oriented 45^{o} down from the horizontal plane containing the ranging arm and 30^{o} from the vertical plane containing the ranging arm towards the cutting drum.
7. Sprays n2 to n5 were modelled 0.1 m apart inclined 8^{o} from the vertical plane perpendicular to the ranging arm and 60^{o} downwards from the horizontal plane.
8. Sprays n6 and n7 were modelled 0.1 m apart parallel to the vertical plane perpendicular to the ranging arm and inclined 60^{o} downwards from the horizontal spray.

Shearer Clearer Sprays: The head-gate (HG) shearer clearer arm consisting of 17 sprays was about 4.57 m long and it was placed at an angle of 8^{o} from the vertical plane away from the coal face (Figure 7(a)). The first four sprays were placed at the tip of the



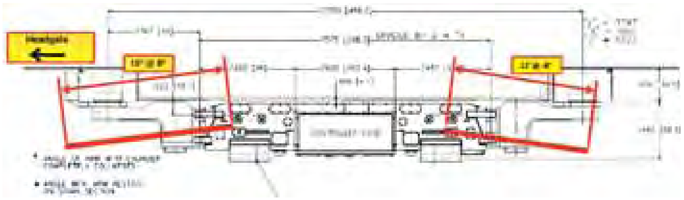
(a)

(b)

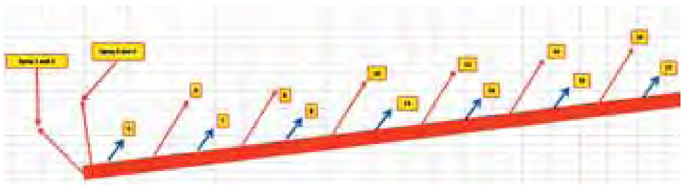
Figure 6. *Spatial distribution of (a) the proposed chassis sprays and (b) proposed ranging arm sprays*

shearer clearer arm. Two of them were inclined 45^{o} from the vertical plane perpendicular to the shearer clearer arm out of which one was inclined 45^{o} upwards from the horizontal plane and the second one was inclined 45^{o} downward from the horizontal plane. The remaining two were inclined 8^{o} from the vertical plane perpendicular to the shearer clearer arm. One was inclined about 45^{o} upwards and the second one was inclined 45^{o} downwards from the horizontal plane. The remaining twelve were inclined 45^{o} upwards from the horizontal plane with the sprays marked red inclined 40^{o} from the vertical plane perpendicular to the shearer clearer towards the tail gate and sprays marked blue inclined 45^{o} towards the tail gate. All sprays were spaced about 0.30 m apart. The spatial distribution and orientation of these sprays are shown in Figure 7(b).

Similarly, the tail gate (TG) shearer-clearer was a mirror image of the HG shearer-clearer as far as the spatial distribution of sprays was concerned, but the orientation of sprays was similar to the HG shearer-clearer arm. Furthermore, the TG shearer-clearer arm was only 3.66 m long containing 12 sprays placed 0.30 m apart. Sprays 1-5 of the HG shearer-clearer arm were omitted from the TG shearer-clearer arm. It is important to discuss here the need for shearer-clearer arm and sprays around the TG drum. It is typical to have two shearer operators. Where the memory cut is working and the shearer is travelling from the tailgate toward the headgate, the TG operator can stay further away from the drum to minimise exposure to dust-laden air. However, if the memory cut is not working, shearer-clearer around the TG drum is very useful to minimise dust exposure.



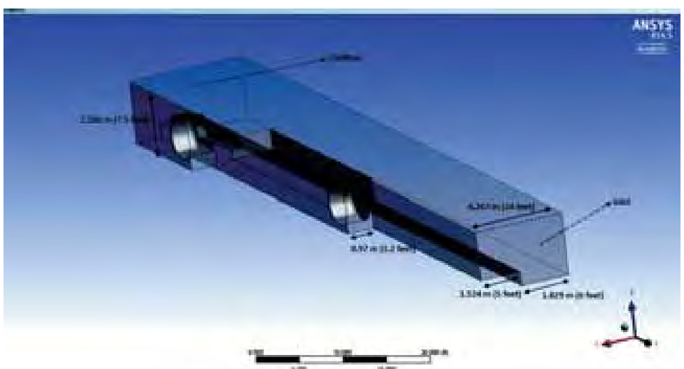
(a)



(b)

Figure 7. *(a) Schematic view and (b) spatial distribution and orientation of the proposed shearer-clearer sprays*

A simplified model of the actual longwall face (Figures 8(a) and 8(b)), similar to that used to analyse currently practiced spray system on a shearer (Chandna, 2015),was used for studying the modified spray system. The length of the model was around 27.43 m with 9.14m in front of the cutting edge of the HG drum and 3.05 m behind the TG drum. The cutting height was 1.98 m and the width of the model from the face to the back edge was about 4.27 m, out of which approximately 0.91 m was the cutting width. Shearer cutting drums were rotated at 60 rpm. Simulations were made using a “Stochastic Random Walk” (ANSYS Inc., 2014) model. This model includes the effect of instantaneous turbulence velocity fluctuations on particle trajectories using stochastic methods. Airflow patterns affected by sprays were analysed in different model cross-sectional planes.



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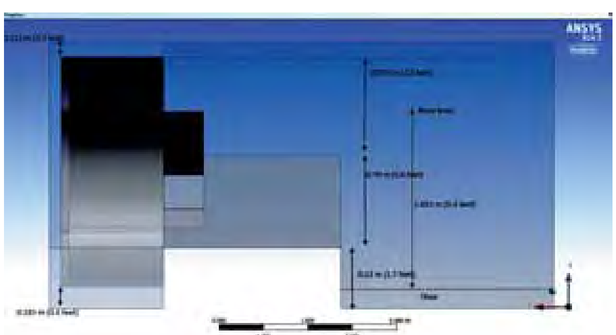


(b)

Figure 8. *(a) 3-D view and (b) side view of the simplified longwall model*

Airflow patterns for a horizontal plane at the nose level (1.615 m) of the operators are shown in Figure 9. The results of simulation of the proposed spray system are summarised below:

1. The intake airflow velocity of around 2.3 m/s is relatively uniform till the chassis body is encountered after which there is a sudden increase in velocity to 3.2 m/s above the shearer due to the turbulence caused by air moving in all directions after interacting with the shearer body and to 2.6 m/s in the walkway region.
2. Air velocities over the chassis body reduce from about 3.2 m/s to about 2 m/s as the air flows over the chassis body.
3. The airflow velocities in the vicinity of the cutting drums as well as the coalface range 1.3 to 1.64 m/s.
4. A better split in intake air over the chassis is seen as compared to the current spray system due to the designed venturi effect created by the shearer-clearer sprays.
5. The higher velocities over the chassis body after the air splits as well as slightly lower velocities in the walkway are attributed to the airflow patterns developed through the designed venturi effect.

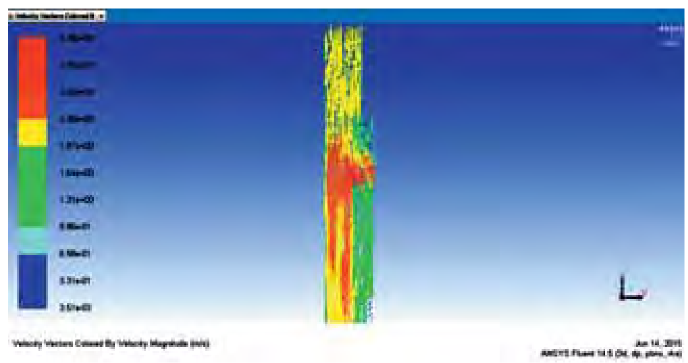
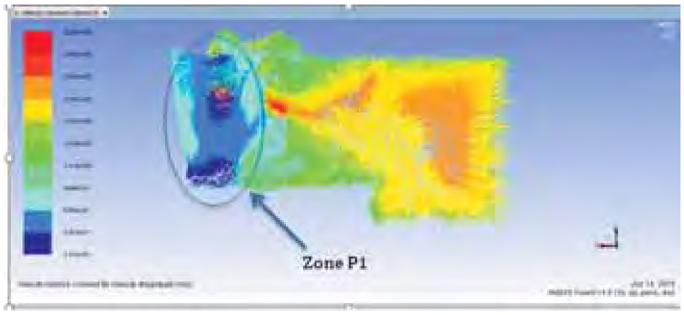


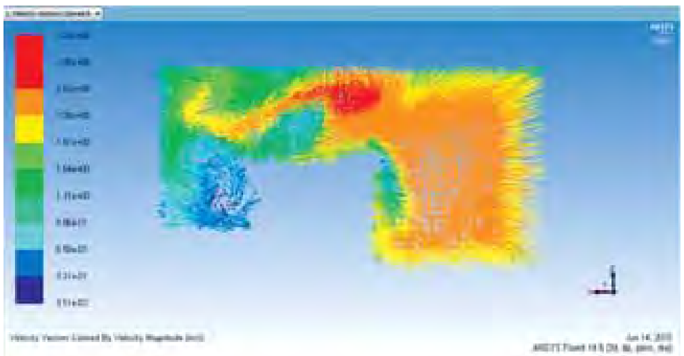
Figure 9. *Airflow patterns at the nose level of the operators for proposed spray system (Grid: Velocity magnitude)*

Airflow patterns in some vertical cross-section planes are shown in the Figures 10(a) and 10(b). The grid in these figures represents the velocity magnitude.

1. Around 0.91 m - 1.52 m away from the start of the chassis body towards the inlet, a low velocity recirculation zone (Zone P1) is observed. However, most of the dust-laden airflow is directed upwards due to the ranging arm sprays and should not affect the exposure of mine operators.
2. A part of high velocity fresh airflow is seen directed towards Zone P1 due to the air split created by the shearer clearer sprays. This prevents the coal dust from travelling toward the walkway.
3. Around the HG operator location, the RC over the chassis body that existed in the current spray system is notably absent.
4. Although the other RC and LV zones in the vicinity of the face (quite close to the bottom of the shearer) are still present, due to the slight movement of air towards the face caused by the venturi effect, the coal dust has no means of mixing with the fresh air in the walkway.
5. A high velocity/pressure zone created around 0.46 m above the

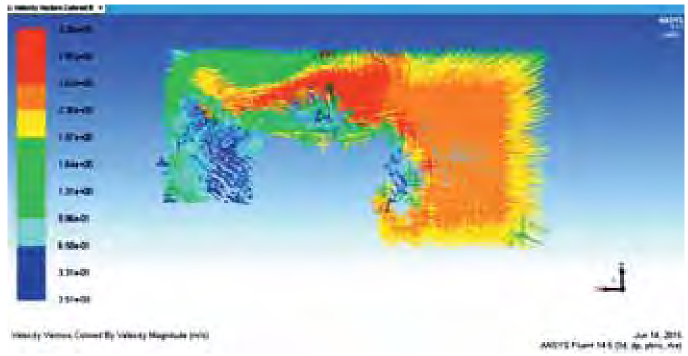


(a)

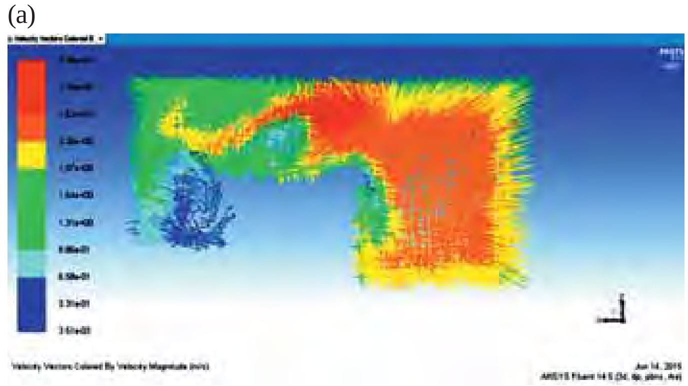


(b)

Figure 10. *Airflow patterns (a) 1.22 m ahead of the chassis body and (b) 0.91 m ahead of the HG operator towards the inlet*



(a)



(b)

Figure 11. *Airflow patterns (a) 0.91 m ahead of the TG operator and (b) at the location of TG operator*

shearer body near the HG operator location also prevents the movement of the dust towards the operator.

6. A similar pattern is observed around the TG operator with the air coming from the face being pushed upwards and back towards the face due to the presence of the TG shearer clearer arm (Figure 11(a)).
7. However, there is more influx of air from the face towards the TG shearer clearer as compared to the HG shearer clearer (Figure 11(b)). However, the dust concentration would be much lower as most of the dust would be removed at the RC patterns existing near the face.

DUST DISPERSION STUDIES

Particles were injected into the model using a Rosin-Rammler logarithmic diameter distribution to model a different mass flow rate for each particle size (ANSYS, Inc, 2014). This distribution is based on the assumption that an exponential relationship exists between the particle diameter and the mass fraction of particles with diameter larger than that. The particle size distribution of the coal dust used for spray system analysis is shown in Figure 12(a). This dust was collected from an operating longwall mine. The size distribution histogram is also shown in Figure 12(a). These data were used to incorporate values of the variables. For modelling the dust particles, only gravitational, drag, and lift forces were considered to be significant. Virtual mass and gradient forces become important only when the ratio of density of the fluid to the density of the particles exceeds 0.1, hence these forces were neglected. Similarly, since the temperature of the fluid remains constant, the thermo-phoretic forces were not considered.Since Brownian forces are only significant for laminar flows, they were also neglected (ANSYS, Inc, 2014). Additional assumptions included:

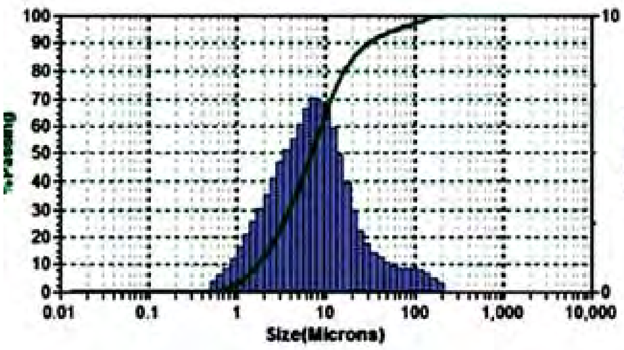
1. Uniform dust injection rate.
2. Spherical dust particles.
3. No particle-particle interaction.
4. No re-suspension of particles into the air-stream.

Dust particles simulated using the discrete phase were assigned the escape boundary condition only on the floor, thus allowing them to settle once they have reached the floor. They were reflected from all other walls such as the sidewall, the roof, the shearer body, etc. as almost all fine dust particles tend to follow the airflow and may be included in recirculation patterns, which might not allow them to settle out. Once the continuous phase converged, a dust concentration of around 200 mg/m^3 of respirable dust was injected from the cutting surfaces as shown in Figure 12(b). This number was based on earlier work of Alam (2006) where respirable dust generated per ton of coal mined by a CM was estimated.

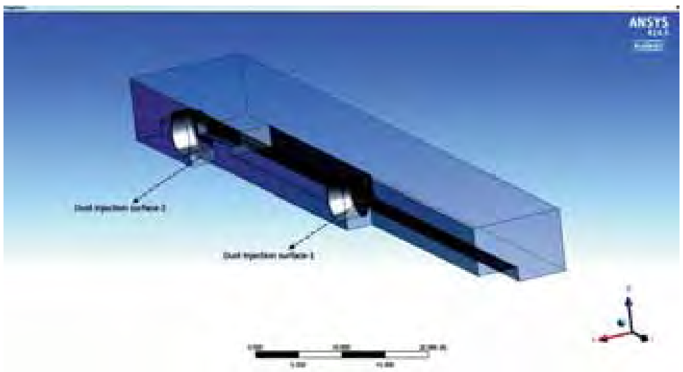
Figures 13(a) and 13(b) represent dust particle tracks, coloured according to the particle diameters, for the currently used spray system and proposed spray system,respectively.

Some of the most relevant results are given below:

1. There is a dust recirculation zone, D1, over the shearer body for the current spray system while it is absent in the proposed spray system.
2. The above observation is consistent with the airflow patterns seen in Figure 15 presented in an earlier paper (Chandna, 2015) for the current spray system and in Figure 9 for the proposed



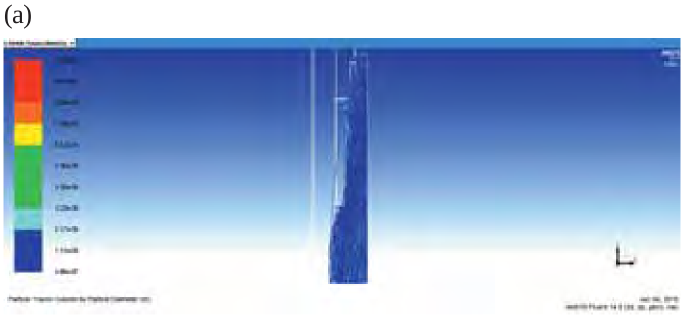
(a)



(b)

Figure 12. *(a) Particle size distribution of the coal dust used for modelling and (b)Dust injection surfaces for longwall face models*

(a)



(b)

Figure 13. *Dust particle tracks coloured by particle diameter for (a) current spray system and (b) proposed spray system*

spray system presented in this manuscript. The proposed spray system eliminates the air recirculation zone present above the shearer body to a large extent.

3. For the proposed spray system, the TG operator is still, to some extent, subjected to dust aerosol although the concentration should be low. Most of the dust that becomes airborne and reaches the operators is very fine respirable dust with diameters in the range of 0.486 to 4.3 microns represented by the bluish dust tracks in Figures 13(a) and 13(b).

SUMMARY OBSERVATIONS

1. Sprays, if placed correctly on the shearer, can be used to prevent the formation of low velocity (LV) and RC zones around the shearer by redirecting the air appropriately.
2. The three-spray configuration consisting of all the sprays placed 0.15 m apart along a straight line (as in a typical chassis spray block) results in significant interaction among sprays as their spray cones intersect with each other and with the airflow. The staggered configurations used in the modified chassis spray block significantly improve the coverage area of a typical spray block and reduce interaction among sprays due to larger distance between the sprays.
3. Since the spray area coverage for the proposed block is much greater than a typical currently used chassis spray block, it can be hypothesised that two sprays placed 0.30 m apart, cause each other to move outwards due to interaction between them, but when a middle spray is placed in between them as in the case of a typical block, it tends to pull the side sprays inwards.
4. The proposed spray system is a significant improvement over the current spray system since it allows more time for wetting and minimises air recirculation zone existing above the shearer body to a large extent. Thus, the HG operator exposure to fine respirable dust particles is reduced. The above statements are based on dust measurements in a simulated longwall dust control facility at the university. Dust reduction of 30-50% in the walkway was achieved at the HG and TG operator locations as compared to current practice. This represents the combined effect of all the modifications made around the shearer.
5. The proposed spray system is able to create the designed venturi effect that facilitates the splitting of the intake airflow and keeps the dust-laden air from entering into the walkway.
6. The TG operator may still be subjected to some amount of coal dust and further improvements in spray design near the TG drum need to be considered.
7. Consideration should be given to moving the TG operator 0.91 m towards the centre of the shearer to further reduce potential to dust exposure.

CONCLUDING REMARKS

CFD modelling shows that with modifications in the spatial distribution and orientations of the sprays, the desired airflow patterns can be achieved which would prevent the movement of the dust particles towards the walkway area. Though further improvements are possible, the proposed modified spray systems look very promising and the coal industry can benefit hugely by its deployment. Some recommendations for additional research improvements are given below.

1. Improve the longwall model by introducing a moving coal carrying conveyor belt and analysing its influence dust

dispersion and airflows below the HG side ranging arm.

2. Include unsteady state modelling of spray systems to include the effect of particle-particle coalescence to study how sprays interact with each other when placed at different distances.
3. Improve the modified proposed spray system to further reduce airflow and dust aerosol travelling toward the walkway.

ACKNOWLEDGMENTS

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An evaluation of fuels and retrofit diesel particulate filters to reduce diesel particulate matter emissions in an underground mine

M.C. Wattrus [1], M. Biffi [2], C.J. Pretorius[3] and D. Jacobs[4],
[1]Sasol, South Africa, [2]Anglo American, South Africa, [3]CSIR, South Africa, and [4]Deutz Dieselpower, South Africa

ABSTRACT

This paper explores what potential exists for South African underground mines to reduce diesel particulate emissions, where the starting point is a mine using older engine technology (Tier 1 emission level compliant) and a diesel containing 500 ppm sulphur. Comprehensive engine exhaust emissions tests were carried out in a test cell on seven diesel fuels and two retrofitted diesel particulate filters. For each evaluation, the engine was operated over a legislated non-road steady-state test cycle and a real-world transient cycle. The transient cycle was obtained from a recording of a working Load-Haul-Dump vehicle in an underground mine, which was used to replicate real-world emissions in a controlled environment. The emission data thus obtained was used also to assess the effectiveness of current dilution rates used in a typical underground mechanised platinum mine to meet proposed occupational exposure levels.

Keywords: *diesel particulate matter, controlled environment, occupational exposure levels.*

BACKGROUND

Improving the health and safety of underground miners by reducing their exposure to hazards has been a major driver behind the increasing prevalence of mining mechanisation. In recent years, the negative health effects of worker exposure to emissions from diesel-powered equipment underground have become more conclusive. This has led to many first world countries adopting defined and increasingly stringent occupational exposure levels (OEL) for diesel particulate matter (DPM) emissions in underground mines. The South African legislators will soon be following this example. Once implemented, non-compliance with this OEL will result in mining operations being halted. It is therefore prudent for South African underground mines to seek proactive solutions to lower DPM emissions from diesel-powered equipment.

The industry-wide collaborative project partly described in this paper explored, amongst other objectives, the potential for the reduction of DPM emissions in South African underground mines using current engine technology, filtration systems, fuel quality and applied fresh air dilution rates. The starting point is defining the operation of an older technology engine (Tier 1 emission level compliant) using diesel fuel containing 500 ppm sulphur as a baseline case. Comprehensive engine exhaust emissions tests were carried out in a test cell using seven different diesel fuels with and without two retrofitted diesel particulate filters. For each evaluation, the engine was operated over a legislated non-road steady-state test cycle and a real-world transient cycle. The transient cycle was obtained from recording the working cycle of a Load-Haul-Dump (LHD) vehicle in an underground, narrow reef platinum mine, which was used to generate real-world emissions results for each evaluation.This data then provided the inputs to model underground air quality for a platinum mine, which was compared against existing and future occupational exposure levels.

OBJECTIVE

The objective was to evaluate the effectiveness of seven fuels and two retrofitted diesel particulate filters (DPF), while recording other exhaust emissions to assess feasible short-term to long-term strategies for the effective reduction and management of diesel particulate matter emissions in underground mines. The recorded variation of DPM emissions was quantified in terms of fresh air dilution factors currently employed in underground platinum mines.

EXPERIMENTAL METHOD

This section provides details of the test engine, evaluated retrofit exhaust after-treatment products, and test fuels. A detailed description of the test protocol is also given below.

Test engine

One of the most prevalent engines in the Platinum mines considered for this test is the Deutz BF 6M 1013 E engine (Tier 1 emission level compliant), which was therefore selected for this project. The basic details of this engine are provided in Table 1.

Table 1. *Test engine specifications*

Engine model	Deutz BF 6M 1013 E
Emission level	Tier 1
Type	6 cylinder, water-cooled, turbo-charged
Displacement	7.146 L
Compression ratio	17.6
Injection system	Single injection pumps for each cylinder
Power rating	137 kW @ 2300 rpm
Torque rating	702 Nm @ 1400 rpm

Retrofit exhaust after-treatment selection

The selection of exhaust gas after-treatment systems suited for retrofitting onto an LHD depends on various requirements. Engine emission performance varies from manufacturer to manufacturer, with operational cycles, fuel, oil and additive quality and the engine emission certification level (Tier 1 to 4, or Stage 1 to 4). As such, after-treatment needs to be selected on a case by case basis for each engine family.

There is a large range of approved after-treatment retrofit suppliers that can be found on the VERT® list (an association dedicated to the promotion of "Best Available Technology" for emission control), the US EPA Verified Technologies List for Clean Diesel, or the US Mine Safety and Health Administration (MSHA) website. After-treatment systems that are not listed on one of these lists have not had their performance independently certified, and should be avoided.

The two exhaust after-treatment options that have been selected by Deutz Dieselpower for the evaluation are described below.

Partial flow SMF®-CRT®

The efficiency of the partial flow diesel particulate filter (DPF) is claimed to be between 30-60% depending on raw exhaust gas composition and soot load. The system is based on a continuous regenerating trap (CRT) design and utilises a sintered metal filter (SMF). Due to the diesel oxidation catalyst (DOC) integrated in this unit, the fuel sulphur content is restricted to a maximum of 50 ppm but an extended life and improved performance will be attained by using 10 ppm diesel. This system uses passive regeneration, i.e. the heat energy in the exhaust stream is used to oxidise the diesel particulate matter trapped in the filter.

Figure 1 below shows the SMF-CRT unit used in the test cell at the Sasol Fuels Application Centre in Cape Town.

Figure 1. *SMF-CRT diesel particulate filter fitted to the engine in a test cell at the Sasol Fuels Application Centre*

Wall-flow SMF®-AR®

The efficiency of the electronically controlled wall flow actively regenerating (AR) sintered metal (SMF) DPF is claimed to be 99%. It makes use of a fuel borne catalyst (FBC) which is an organometallic chemical compound that is dosed into the vehicle's fuel tank during operation. This FBC, along with electric heaters integrated in the unit, allows the DPF to actively regenerate, or burn-off, the trapped DPM under almost any conditions. The system contains no platinum group metals which allow its operation with high sulphur diesel fuels.

Figure 2 shows of the SMF-AR unit installed in the test cell at the Sasol Fuels Application Centre.

Test fuels

Another objective of these collaborative tests was the evaluation of fuels that have the potential to reduce DPM emissions. The base-line case was a SANS 342 compliant diesel fuel containing 500 ppm sulphur, as this represents currently the most widely used fuel in the commercial sector due to cost. The selection of the other fuels in the tests was hypothesised on the assumption that that they would yield reductions in diesel particulate matter emission due to their inherent properties.

Figure 2. *SMF-AR diesel particulate filter fitted to the engine in a test cell at the Sasol Fuels Application Centre*

The full fuel analyses completed showed that all fuels were supplied to specification, with two exceptions. These were the 500 ppm and 50 ppm diesel fuels which were intentionally blended up to their respective limits. These fuels exceeded the SANS 342 sulphur limits slightly, but were considered acceptable for the purposes of these tests to demonstrate the effect of sulphur on emissions.

European certification diesel

Since the test engine would have been certified in Europe against the relevant legislation, a diesel fuel conforming to the European specification EN590 was included to ensure the engine was compliant prior to the start of testing. (Test fuel name: EN590)

500 ppm diesel

This is a crude oil-derived South African diesel containing 500 ppm sulphur (SANS 342 compliant). This test fuel was produced at the NATREF refinery in Sasolburg. It was intentionally blended up from around 300 ppm to the 500 ppm limit with high sulphur diesel for the purposes of this project. Sulphur content in typical market fuels varies quite considerably so the decision was taken to fix the content at the upper limit of the SANS 342 specification to determine the effect of sulphur on various emissions. This test fuel was blended and supplied by Sasol. (Test fuel name: 500 ppm)

50 ppm diesel

This is a crude oil-derived South African diesel containing 50 ppm sulphur (SANS 342 compliant). The base fuels used to arrive at this blend were the Euro-pean certification diesel and the 500 ppm diesel fuels. Consisting largely of the EN590 compliant diesel fuel, this product was blended up to the 50 ppm limit of the low sulphur diesel grade in South Africa. It is important to note that this fuel will typically exhibit a lower final boiling point and lower aromatic content than SANS 342 compliant diesel fuels. This test fuel was blended and supplied by Sasol. (Test fuel name: 50 ppm)

Sasol turbodiesel TM ULS 10 ppm diesel

This is a fully-synthetic South African diesel fuel containing less than 10 ppm sulphur (SANS 342 compliant). This test fuel was sourced from a Sasol fuel retail site directly outside the Sasol refinery in Secunda. (Test fuel name: 10ppm)

Sasol GTL diesel

This is a highly-paraffinic synthetic diesel containing less than 10 ppm sulphur. This commercially available GTL (Gas-to-Liquid) diesel fuel was obtained from the ORYX GTL production facility in Qatar, where Sasol is the technology supplier and equity partner. This fuel meets the requirements of the EN15940 specification. (Test fuel name: GTL)

50 ppm diesel with 7% SME biodiesel

Soy methyl ester (SME) was added to 50 ppm diesel base, at a 7% v/v ratio to generate this biodiesel fuel mixture. This blend ratio was guided by the maximum allowable limit imposed by most engine manufacturers. (Test fuel name: SME7)

50 ppm diesel with 7% PME biodiesel

Palm oil methyl ester (PME) was added to 50 ppm diesel base fuel, at a 7% v/v ratio to generate this biodiesel fuel mixture. This blend ratio was guided by the maximum allowable limit imposed by most engine manufacturers. (Test fuel name: PME7)

Laboratory analytical equipment

In addition to the instrumentation used for measuring engine torque and speed, pressures, temperatures, and air flow rates, the following specialised instrumentation was employed during the tests:

- Fuel consumption was measured using a mass flow meter employing a Coriolis-mass flow sensor and fuel temperature conditioning (AVL735S and AVL753C).
- All testbed data as well as engine control module (ECM) parameters were logged by the test cell automation system at a frequency of 10 Hz.
- Raw exhaust gas was sampled simultaneously before and after the DPF to measure concentrations of NOx (nitrogen oxides), CO (carbon monoxide), THC (total hydrocarbons), and CO_2 (carbon dioxide) using standard raw gas emissions benches (Horiba MEXA Series 7000).
- Dilute and bag emission measurements were made from a CVS (Constant Volume Sampler, Horiba CVS7000), using a dilute emissions bench (Horiba MEXA series 7000).
- A double dilution system with a full flow primary dilution tunnel, conditioned primary and secondary dilution air, and single, heated, 47 mm diameter sample filters was used for particulate sampling.
- Particulate matter (PM) sample filters were pre-conditioned in a humidity and temperature controlled room before the pre- and post-test weighing. A Mettler Toledo XP2U microbalance (readability of 0.1 µg) was used to weigh each filter.
- Pre- and post- DPF speciated emission measurements were made by means of two on-line FTIR (Fourier Transform Infra-red) analysers (Peus SESAM).
- Real-time measurements of soot concentration in the undiluted exhaust were performed by means of a photo-acoustic soot sensor (AVL483 Micro Soot Sensor). Soot measured in this way corresponds to the insoluble or non-volatile portion of the particulate matter (primarily elemental carbon).
- Particle number emissions were measured in the dilution tunnel with a PMP (Particle Measurement Programme) compliant system that comprises an engine exhaust condensation particle counter (TSI 3790), and Dekati DEED 300 dilutor.
- Exhaust samples were also collected directly from the exhaust pipe onto a quartz-fibre filter using a mini dilution tunnel for post analysis using the NIOSH 5040 method. This method determines the mass of elemental and organic carbon captured on the filter using thermal-optical analysis.

Test protocol

All engine tests were performed with the engine fully warmed up, and, where applicable, emission tests were conducted in compliance with EPA emission standards for non-road diesel engines (published in the US Code of Federal Regulations, Title 40, Part 89). The US non-road emission standards are harmonized to a certain degree with European non-road emission standards.

For Tier 1 to 3, non-road engine emissions are measured on a steady-state test cycle that is equivalent to the ISO 8178 C1, 8-mode steady-state test cycle. This cycle is also known as the non-road steady cycle (NRSC). There is an additional requirement for Tier 4 compliant engines to measure emissions on the non-road transient cycle (NRTC). As the selected test engine complies with Tier 1 emission standards, only emissions compliance over the non-road steady-state test cycle was established.

As part of the project's objectives, there was a need to measure emissions over a real-world transient duty cycle for a LHD vehicle. The test cycle approximating real-world operation was obtained by recording the operation of an LHD at Anglo Platinum's Bathopele mine using a portable data logger (VBOX IISX data logger). The recorded data was replicated in the engine test cell using a transient dynamometer. Figure 3 shows the logger mounted on the LHD.

Figure 3. *Data logger mounting position on LHD at Bathopele mine in Rustenburg*

Some 17 hours of data were recorded over the course of one and a half shifts. In consultation with the project members, a representative segment was extracted from this dataset and used as the under-ground mining transient cycle (UMTC). The extracted test cycle contained a balanced quantity of repetitive idle, loading, hauling, and dumping segments. Figure 4 shows the speed and load profiles for the selected 24 minute test cycle.

All fuels and DPFs were evaluated by subjecting the test engine to the above transient cycle. This generated the primary dataset that was used for comparison. Although the transient cycle represents a

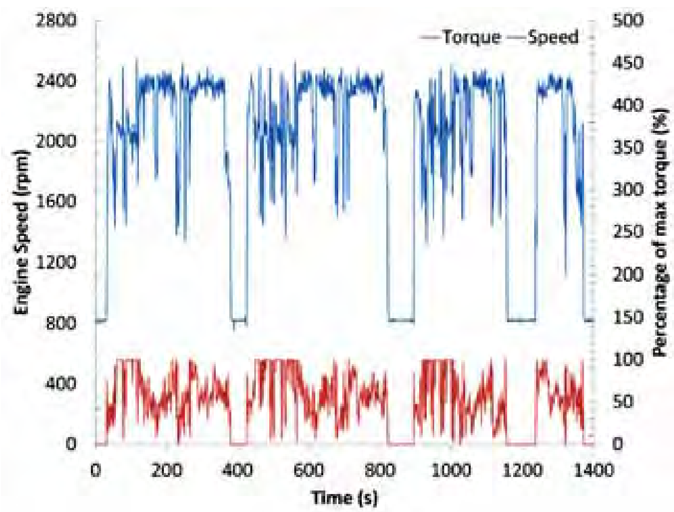

Figure 4. *Speed and torque profile of the selected underground mining transient cycle*

close approximation of real-world operation, it cannot fully guarantee that real-world emissions will be reproduced accurately. Only a direct comparison of emissions recorded on vehicles and during engine test cell runs may be used to verify accuracy. The legislated non-road steady cycle was also used during the evaluations in order to assess the level of emissions compliance against the Tier 1 certification limits. Table 2 shows the torque and speed set points for this test cycle.

Table 2. *Non-road steady cycle*

Mode Number	Speed (rpm)	Load (%)	Torque (Nm)	Weighting Factor
1	2300	100	Max	0.15
2	2300	75	393	0.15
3	2300	50	262	0.15
4	2300	10	52	0.1
5	1500	100	Max	0.1
6	1500	75	483	0.1
7	1500	50	322	0.1
8	1500	10	Idle	0.15

The maximum torque values (524 nnd 645 Nm for the 2300 and 1500 rpm speeds, respectively) in Table 2 were determined during a power curve test using the European certification diesel fuel described in section 3.3. These set-points were used also for the other test fuel runs. The expectation was that the other fuels would produce varying torque values at maximum load based on the fuel's volumetric energy density.

Test sequence

This project was separated into two phases which allowed a more focused assessment of each option's ability to reduce diesel particulate matter (DPM) emissions. Phase 1 focused on a fuel-only solution where no capital investment would be required to reduce DPM emissions. In this phase, no exhaust after-treatment was used during the engine test runs to assess the engine's emissions in its original Tier 1 specification. All seven test fuels detailed in section 3.3 were evaluated in Phase 1 using a pseudo-randomised test sequence, shown in Table 3. Results presented later in the paper are the average of the three tests and error bars indicate the data's standard deviation. Student's T-test (95% confidence level) was used to determine whether differences between the averaged results were statistically significant or not.

Table 3. *Fuel only evaluation test sequence*

Test block 1	Test block 2	Test block 3	Test block 4
EN590	EN590	EN590	EN590
500ppm	SME7	GTL	
50ppm	10ppm	PME7	
10ppm	PME7	SME7	
GTL	500ppm	10ppm	
SME7	50ppm	50ppm	
PME7	GTL	500ppm	

It can be seen that EN590 diesel was always tested first in each test block and was used again a fourth time. This was done intentionally to check if any drift occurred throughout the test sequence and constituted a "bracket test" to ensure the engine was performing in the last test at a similar level as the first test.

Phase 2 focused on the evaluation of the performance of two retrofitted DPFs and was aimed to provide a hardware solution to reduce DPM emission while using cost-effective and freely available market fuels that meet the minimum requirements of the DPFs. The SMF-CRT required a diesel fuel that contains less than 50 ppm sulphur and therefore, the 50 ppm and 10 ppm diesel fuels were used. The SMF-AR was tolerant of high sulphur diesel fuels and was thus tested with the 500 ppm, 50 ppm, and 10 ppm diesel fuels. Table 4 and Table 5 show the test sequences for Phase 2.

Table 4. *SMF-CRT evaluation test sequence*

Test block 1 (ppm)	Test block 2 (ppm)	Test block 3 (ppm)	Test block 4 (ppm)
50	10	50	10
10	50	10	

Table 5. *SMF-AR evaluation test sequence*

Test block 1 (ppm)	Test block 2 (ppm)	Test block 3 (ppm)	Test block 4 (ppm)
500	50	50	10
50	10	500	

Due to the limited number of test fuels in each of these evaluations, drift was not checked at the start of each test block, as in the Phase 1. However, a bracket test on 10 ppm diesel was included, and the conventional gravimetric sample filter paper, used to sample diesel particulate matter from the full flow dilution tunnel, was replaced with a quartz-fibre filter in order to measure the ratio of elemental to organic carbon using the NIOSH 5040 method with each DPF technology. This analysis was also done in Phase 1 but the sample was drawn directly from the exhaust pipe.

Each fuel evaluation for Phases 1 and 2 entailed testing the fuel, with the engine fully warmed up and running, over the non-road steady cycle and the underground mining transient cycle. At each fuel change, the fuel system was flushed using the next test fuel. Thereafter, a pre-conditioning test was run on the engine before starting the evaluation of the next test fuel.

RESULTS AND DISCUSSION

Engine condition and operation

The Deutz BF6M1013E engine used in this study is one of the most prevalent engines in Anglo Platinum's mines. The specific engine that was used in the test cell was originally new, but under-went a severe run-in period at the Deutz Dieselpower work-shop before being supplied to Sasol for testing. This is an important step to ensure that the engine will not introduce any drift in the emissions results between the first and last tests.

The health of this engine was considered to be very good and, as expected therefore, it was found to be fully compliant with Tier 1 emission limits. As the engine ages, an increase in the emissions can be expected but should, according to the emission requirements for which it is approved, remain compliant for the duration of the engine's useful life. According to the US Environmental Protection Agency (EPA), the useful life of a non-road engine with a power rating above 37 kW is 8000 hours or 10 years, whichever occurs first.

In order to approximate deterioration of engines' combustion efficiency over time and effect of less than adequate maintenance, deterioration factors (DF) were applied to the emission limits. For the purpose of these tests, the DFs were introduced to impact directly on the emitted mass of gases and particulates:

- DF1: for new engines; Factor = 1.0;
- DF2: for well-maintained engines at the end of their useful life; Factor = 1.2;
- DF3: For poorly maintained engines at the end of their useful life; Factor =1.5.

It must be noted that DFs are specific to each engine and are to be determined by the engine manufacturers in accordance with good engineering practices. In the USA, for example, deterioration factors are subject to EPA approval. Typical DFs will not exceed 1.2 (20% increase) for older engine technology since the absolute emission limits are relatively high. A DF of 1.2 is realistic for a well maintained engine at the end of its useful life. When maintenance is not rigorously carried out in an under-ground mine, there could be a much larger deterioration in emissions. A comprehensive maintenance plan based on an engine OEM's advice, which is verified through routine in-field emission condition monitoring, is crucial to ensure high underground air quality is maintained. Failure to ensure that the engines are well maintained, will undo any improvement made by retrofitting exhaust after-treatment or switching to a low emission diesel fuel.

Fuels evaluation

The seven diesel fuels evaluated during this study represented a selection of commercially available as well as of a few alternative fuels. The emission results showed the extent of possible improvements achievable by mines even only by switching fuel type for an existing vehicle fleet. This by no means represents the limit of what can be accomplished with a "fuel-only solution" as there are other fuel formulations that will further reduce emissions. However, these formulations are typically not commercially available yet, or will, in addition to a higher cost price, introduce significant handling and operational challenges.

Although reduction of DPM emissions was the primary objective in this study, emphasis was also placed on limiting emission levels of other pollutants and at containing fuel consumption.

Emissions performance

As outlined in the experimental setup section, all regulated engine emissions (DPM, NOx, CO, THC) and speciated emissions (e.g. NO_2, NO, SO_2, etc.) were measured during testing, however due to the large quantity of data only DPM, CO, NO_2, and SO_2 will be presented below as they specifically pertain to the occupational exposure levels that are set to govern air quality.

Diesel particulate matter emissions

The engine's particulate matter (PM) emissions, which were the primary focus in this research work, comprise four major portions: (1) carbonaceous particulates (also known as soot or elemental carbon), (2) liquid hydrocarbons that are adsorbed onto the carbon particles and are referred to as the organic carbon (OC) portion or the soluble organic fraction (SOF), (3) sulphates (SO_4) and bound water, and (4) ash (inorganic material).

PM emissions measured during the tests are presented in Figure 5 in relation to the base-line fuel's emission levels.

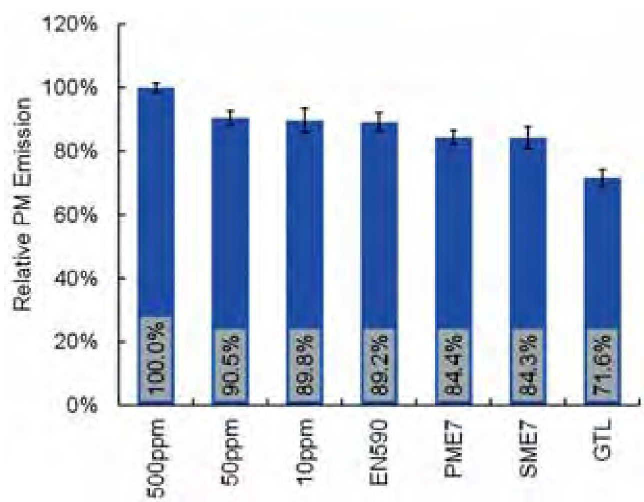

Figure 5. *Relative PM emissions for a LHD fitted with a Deutz BF6M1013 engine*

The results showed that diesel PM emissions were reduced by approximately 10% when switching from a diesel containing 500 ppm sulphur to ultra-low sulphur diesel (50 ppm, 10 ppm, or EN590 diesel). A further reduction of 5% was achieved when adding 7% biodiesel (SME or PME) to 50 ppm diesel; a similar benefit would have been observed if the biodiesel were added to the EN590, 10 ppm, or 500 ppm diesel fuels. The largest reduction was recorded when switching to a highly-paraffinic synthetic diesel (GTL diesel), where PM emissions were reduced by 28.4% when compared to the 500 ppm diesel level.

All fuels produced emissions below the Tier 1 emission limit. GTL diesel managed to lower the PM emissions to below the Tier 2 and 3 limits.

Diesel particulate matter analysis (using NIOSH 5040) for this engine indicated an average elemental carbon to total carbon ratio of 0.71 for all fuels, and an average elemental carbon to total particulate matter ratio of 0.60.

NIOSH 5040 showed reductions in the mass of PM that corresponded well with the gravimetric PM results presented in Figure 5.

Carbon monoxide emissions

Carbon monoxide (CO) emissions are formed mainly due to incomplete combustion, which is exacerbated by lack of oxidants, reduced temperature, and shortened residence time. As combustion proceeds to completion, oxidation of CO to CO_2 occurs through recombination reactions between CO and various oxidants. If these recombination reactions are incomplete due to a lack of oxidants or due to low gas temperatures, CO will be left without oxidation (Henein and Patterson, 1972).

CO emissions are presented in Figure 6.

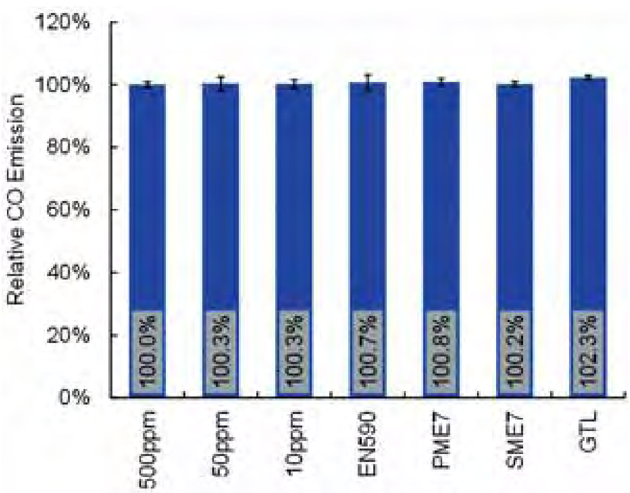

Figure 6. *Relative CO emissions for a LHD fitted with a Deutz BF6M1013 engine*

CO emission results showed no statistically significant difference between fuels. Furthermore, CO emissions from the test engine in this study, for all fuels, were substantially below the Tier 1 limit, and well under the Tier 4 limit.

Nitrogen dioxide emission

Nitrogen dioxide (NO_2) on its own is not a regulated exhaust emission that engine manufacturers are required to limit; rather NOx is regulated as the sum of NO_2 and nitric oxide (NO). NO_2 is, however, regulated in restricted ventilation environments by various occupational health and safety laws around the world.

NO_2 emissions are presented in Figure 7.

Due to the very low concentration levels, and therefore poor repeatability in measuring NO_2, there were no statistically significant differences between fuels. There was, however, a general increase in these emissions from all fuels when compared to 500 ppm diesel.

Sulphur dioxide emissions

Similar to NO_2 emissions, sulphur dioxide (SO_2) emissions are also not a regulated engine exhaust emission. SO_2 emissions are effectively controlled by reductions in the fuel sulphur levels. When Tier 1 emissions legislation were promulgated, the diesel fuel sulphur levels were between 3000 ppm and 5000 ppm; currently in South Africa there are two grades of diesel, 500 ppm and 50 ppm.

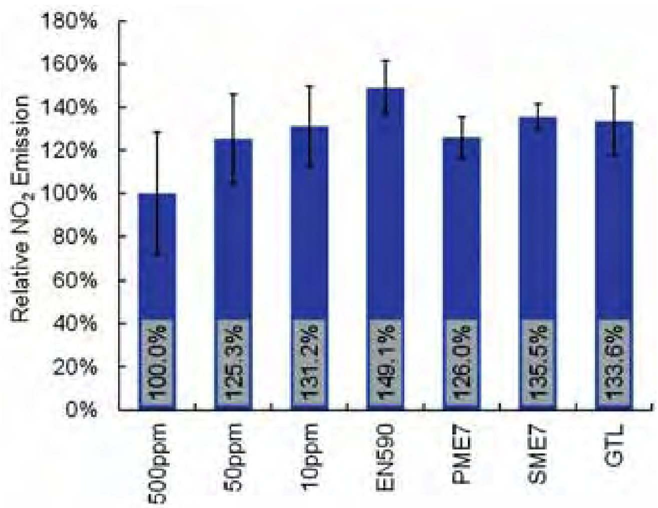

Figure 7. *Relative NO_2 emissions for a LHD fitted with a Deutz BF6M1013 engine*

The effect of lowering fuel sulphur levels from 500 ppm to less than 10 ppm on SO_2 emissions is presented in Figure 8.

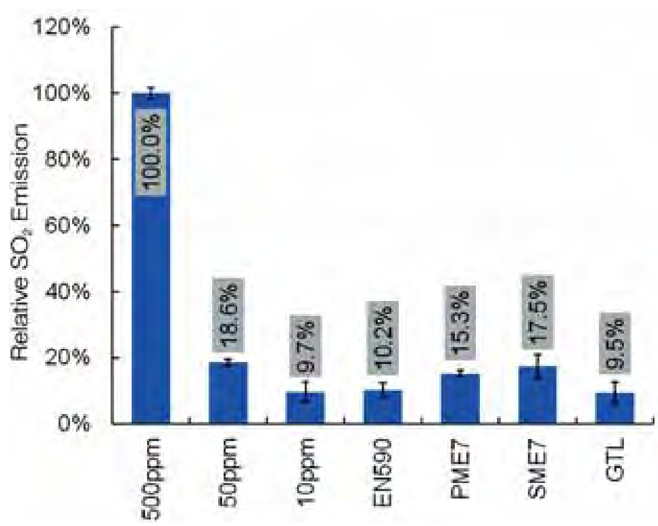

Figure 8. *Relative SO_2 emissions for a LHD fitted with a Deutz BF6M1013 engine*

When lowering fuel sulphur levels from 500 ppm to 50 ppm, an 81.4% reduction in SO_2 emissions was recorded. Lowering fuel sulphur further to 10 ppm effectively halved the SO_2 emissions from 50 ppm diesel. The addition of 7% PME or SME (which are both sulphur-free fuels) slightly lowered the SO_2 emissions of the 50 ppm. There were no statistically significant changes between the 10 ppm, EN590, and GTL diesel fuels, which are all near sulphur-free fuels. The low levels of SO_2 that remain when running an engine on a near sulphur-free diesel are produced from the combustion of the engine lubricant which typically contains sulphurous compounds.

Fuel formulation and additive optimisation

This study focused on selection of conventional diesel fuels that are commercially available in the market. If the cost of retrofitting exhaust after-treatment onto existing vehicle fleets is undesirable, customised fuel formulations and additive optimisation are other avenues available to achieve even greater DPM emission reductions. Some examples are provided below.

Commercially supplied combustion improver additives that claim to reduce DPM emissions can be blended into commercially available diesel (500 ppm, 50 ppm, 10 ppm diesel). These additives are metal-free, completely organic, and added at very low treat rates of less than 300 ppm. This ensures there are no secondary emissions formed after combustion when using them in engines without exhaust gas after-treatment.

After market combustion improver additives are available but are often not metal-free or organic, and are treated at significantly higher dosage rates (dosage rates should typically not exceed 1000 ppm). These products may yield DPM emission reductions, but their secondary emissions potential must be assessed. The combustion of metal-based additives would generate ash particles that pose a health risk unless captured in a diesel particulate filter. Any additive should be registered with institutions such as the United States Environmental Protection Agency (EPA). The EPA requires that all fuels and additives are registered under "40 CFR Part 79 - Fuel and Fuel Additive Registrations (FFARs)". For example, the fuel borne catalyst (satacen®1 produced by Innospec Fuel Specialties) used in conjunction with the SMF-AR diesel particulate filter, which was used in this study, is approved with the EPA. This fuel borne catalyst (FBC) is an organo-metallic chemical compound that must not be used without a wall-flow diesel particulate filter, since the FBC generates ash particles that would otherwise exit into the atmosphere.

Water diesel emulsions are very effective at reducing DPM (and NOx) emissions, although some emissions such as CO may increase, DPM emission reductions up to 70% may be achieved. Any claims regarding improved engine efficiency are likely to be untrue. There are many valid concerns regarding their practical application, these include: applications where high fuel temperatures are experienced (as is the case in most modern, high pressure fuel injection systems, or engines with fuel supply rails built into the engine block - such as the test engine in this study), fuel handling, storage stability, cold weather vehicle operability, power loss, and equipment durability.

Increasing the biodiesel content up to 20% in an ultra-low sulphur diesel will further reduce DPM emissions. This option would have to be implemented in consultation with the original equipment manufacturer (OEM) of the engine, since most OEMs will void warranties when using fuel containing more than 7% biodiesel. High biodiesel blends can increase the rate of oil dilution, will increase volumetric fuel consumption, and increase the likelihood of the biodiesel handling challenges that were highlighted above. GTL diesel and biodiesel blends work very well together, where DPM emission reductions of up to 40% have been measured. This practice negates the need to add lubricity additives to neat GTL diesel.

With all the above mentioned fuel formulations and additives, laboratory testing and validation is critical. In-field testing of new fuels or additives is highly discouraged due to the difficulty in controlling engine load between fuel or additive comparisons repeatedly. Often inaccurate emission analysers are also used which cannot provide a definitive answer required to support a business case.

Diesel particulate filter evaluation

The diesel particulate filter (DPF) evaluation phase of this study assessed the performance of two systems supplied by Deutz Diesel power to reduce DPM emissions, namely the SMF-CRT and SMF-AR diesel particulate filters. The partial-flow SMF-CRT has a claimed efficiency of between 30 to 60%, and has an integrated diesel oxidation catalyst (DOC) which reduces carbon monoxide and unburned hydrocarbons. The wall-flow SMF-AR has a claimed filtration efficiency of 99%, and has no integrated DOC.

Emissions performance

Similar to the fuels evaluation, only DPM, CO, NO_2, and SO_2 will be presented below as they specifically pertain to the occupational exposure levels that are set to govern air quality. The following series of figures compares the performance of the SMF-CRT (shown with a prefix CRT) and SMF-AR (shown with a prefix AR) exhaust after-treatment systems against an engine without after-treatment using 500 ppm diesel.

Diesel particulate matter emissions

Both exhaust after-treatment systems achieved their respective design filtration efficiencies during testing; the actual PM emission reductions are shown below in Figure 9.

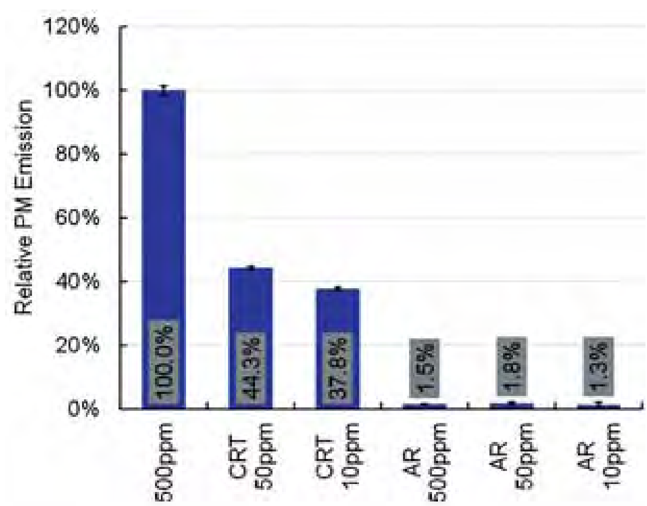

Figure 9. *Relative PM emissions for a LHD fitted with a Deutz BF6M1013 engine with after-treatment fitted*

The SMF-CRT system achieved filtration efficiencies towards the upper bound of its claims in real-world operating conditions; 55.7% filtration efficiency was achieved when operating the engine on 50 ppm diesel, and 62.2% filtration efficiency for 10 ppm diesel. The SMF-AR system also achieved filtration efficiencies around its design claims of around 98% with all fuels tested on it.

Carbon monoxide emissions

CO emissions are presented in Figure 10.

Due to the diesel oxidation catalyst (DOC) built into the SMF-CRT system, reductions in CO and THC emissions were achieved. A reduction of 82.5% was achieved with 50 ppm diesel compared to the base 500 ppm diesel case. 10 ppm diesel further reduced CO emissions to 85.5% below the 500 ppm base case. This represents a 17.1% reduction from the 50 ppm diesel result.

Due to the lack of any DOC function in the SMF-AR, this system did not reduce CO emissions but rather increased them by approximately 20%. It is not fully understood why this occurred,

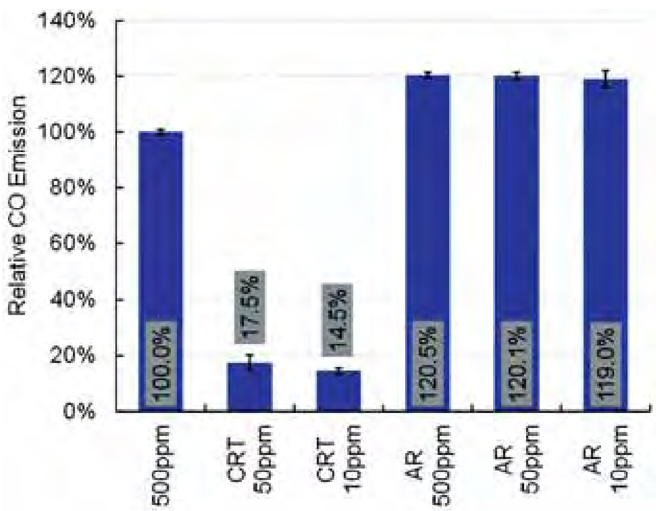

***Figure 10.** Relative CO emissions for a LHD fitted with a Deutz BF6M1013 engine with after-treatment fitted*

but these higher levels of incomplete combustion could be related the increased exhaust backpressure created by the SMF-AR; the SMF-CRT also raised CO emissions before the after-treatment, when compared to operating the engine without after-treatment, but were then substantially reduced over the integrated diesel oxidation catalyst - which the SMF-AR did not have.

Nitrogen dioxide emissions

NO_2 emissions are presented in Figure 11.

The DOC built into the SMF-CRT increased oxidation rates of nitric oxide (NO) resulting in a large NO_2 emission increase was seen compared to 500 ppm diesel levels. This NO_2 emission increase would be similar to one observed in a vehicle fitted only with a DOC, such as is common practice in most underground mines.

The SMF-AR did, however, decrease NO_2 emissions by 99% from levels seen without the SMF-AR fitted.

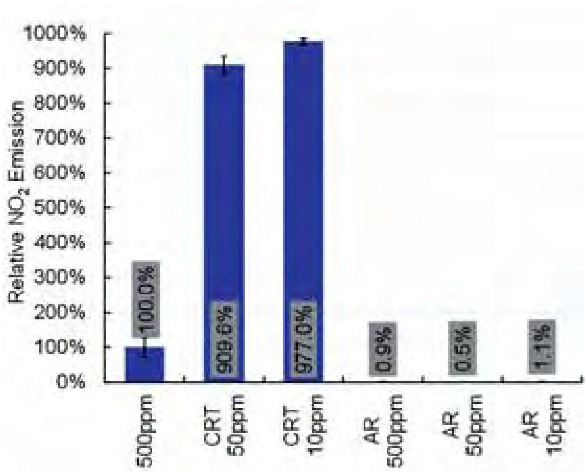

***Figure 11.** Relative NO_2 emissions for a LHD fitted with a Deutz BF6M1013 engine with after-treatment fitted*

Sulphur dioxide emissions

SO_2 emissions are presented in Figure 12.

SO_2 emissions are purely a function of the sulphur content in the fuel and engine lubricant. As a result, the SO_2 emissions with the SMF-CRT were similar to an engine without after-treatment, albeit a little lower.

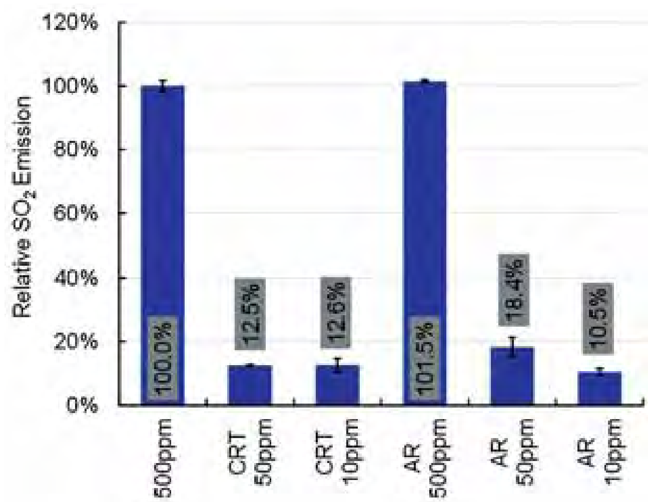

***Figure 12.** Relative SO_2 emissions for a LHD fitted with a Deutz BF6M1013 engine with after-treatment fitted*

Similarly, the SMF-AR could not affect these emissions in any way. Only when switching from 500 ppm diesel to 10 ppm diesel, was a 90% decrease in SO_2 emissions recorded.

Predicted underground mine air quality

In the preceding two sections, several routes to lowering underground emissions were presented; be it a fuel-only solution, or a more capital intensive hardware retrofit solution. It can quickly become a complex decision when deciding which pollutant is a higher priority, while along the way needing to balance the chosen path against fuel consumption penalties. In order to add some context to the raw exhaust emission results presented above, an exercise was carried out where the experimental data were translated into a mass of pollutant emitted underground by one LHD over the course of the operating cycle.

The data sets were used to calculate fresh air volumetric flow rates that would be able to dilute the measured emissions for the different configurations to levels below the occupational exposure levels (OEL) being currently considered by the Department of Mineral Resources for South African mining operations. The goal was to determine levels of compliance for all pollutant OELs, and understand what roadmap could be set up to achieve the impending diesel particulate matter OEL that is set to be progressively reduced over a three year period in South Africa.

LHD emissions per shift

For the purpose of these studies, it was decided to focus on the following pollutants: DPM, CO, NO_2, and SO_2. The engine emission results (in g/kWh) from the 24 minute underground transient test were multiplied by the test cycle work (in kWh), and then divided by 24 to obtain mass of emission per minute of operation.

At this point it is appropriate to distinguish between exposure limits set for deterministic effects, typical of pollutants such as the three gases considered where the effect is based on a well-established response model, and stochastic effects, typical of carcinogenic substances such as particulates in the engine exhaust cocktail, where dose-and-effect relationships are not clear and where exposures should be kept "as low as reasonably possible or achievable" (ALARP or ALARA principles).

The distinction between the two effects is fundamental in establishing minimum ventilation rates. Emission values obtained from the 24 minute underground transient test were adapted to reflect the operational period assumed typical of the LHD vehicle, namely 4 hours and seven minutes, as determined from recorded vehicle data, over anominal eight hour shift. Exposure of workers to gases, response to which is deterministic, would allow excursions above the respective OEL, but below the short term exposure limit or STEL, so that over an eight hour period the OEL is not exceeded (Stanton et al, 2014). However, since "diesel emissions" are deemed to be carcinogenic, this assumption is not valid and the interpretation is that exposures must be below the exposure limit at all times. In actual fact, good practice requires the application of the ALARP principle to ensure that exposure to carcinogens is below such limits.

Fresh air dilution factors

In order to provide guidance as to the required minimum ventilation dilution rates based on these results, the recorded gas and particulate emissions were normalised to average air flow rates based on the respective OELs while considering the qualification indicated above.

For gaseous emissions, dilution rates are invariably very low and reflect the properties of the fuels and of the exhaust after treatment systems used. Figure 13 depicts the indicated fresh air dilution quantities applicable to the test results to meet the OEL for Carbon Monoxide (35 mg/m^3).

Figure 13 indicates the impact of increased exhaust back pressure induced by the use of the active regeneration (AR) DPF requiring additional dilution. The catalytic oxidation effect of the continuous regenerating trap unit (CRT) on the carbon monoxide is also evident from the reduced dilution requirements.

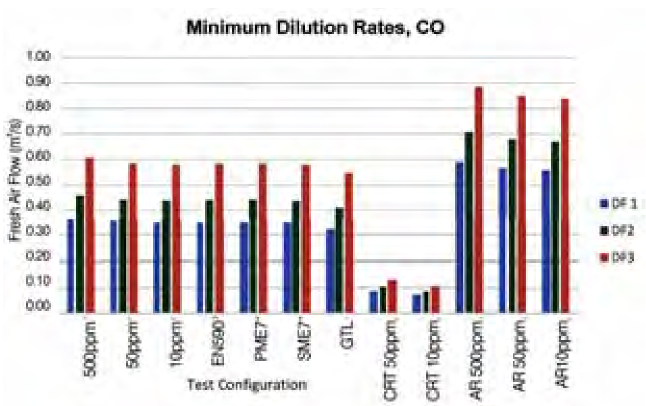

Figure 13. *Fresh air dilution factors for emitted Carbon Monoxide*

Figure 14 summarises the fresh air dilution requirements based on the sulphur dioxide emissions to meet the OEL (5 mg/m^3).

The results indicated in Figure 14 show clearly the effect that the introduction low sulphur fuel has in reducing fresh air requirements.

Figure 15 indicates the required dilution rates to reduce emitted levels of nitrogen dioxide to below the OEL (5 mg/m^3) (Stanton, et al, 2014).

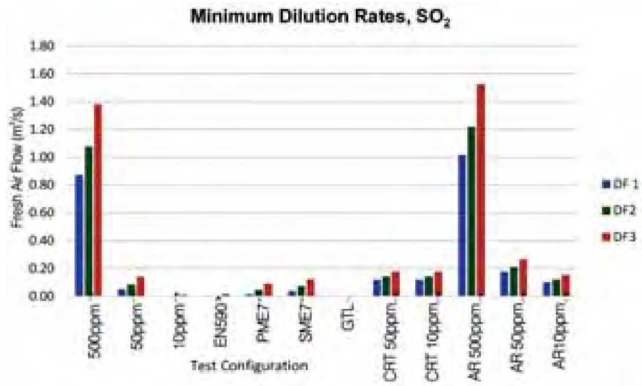

Figure 14. *Fresh air dilution factors for emitted Carbon Monoxide*

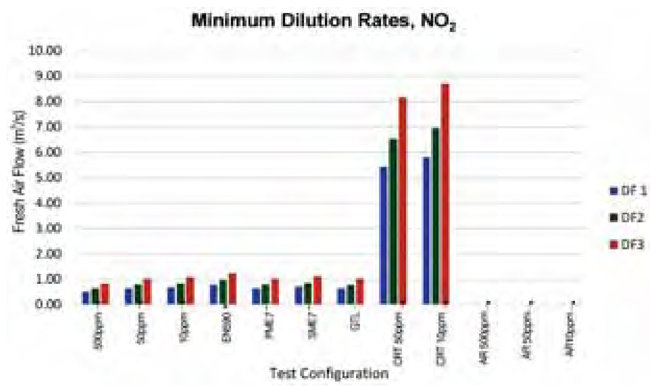

Figure 15. *Fresh air dilution factors for emitted Nitrogen Dioxide*

In deciding air-flow requirements as guided by Figures 13, 14 and 15 one would have to consider the type of fuel utilised, the condition of the engine as well as the type of exhaust after-treatment system employed, if any, and then select the highest flow-rate. The re-use of air used to dilute engines' exhaust streams requires careful consideration as to the gases contained, temperature and humidity of the air for any further use, dilution or mixing down-stream.

A similar analysis was made for the particulate matter emissions. The total measured particulate matter (TPM) measured over one shift was converted to a total carbon fraction for each of the test sets. These results were converted to mass emissions per unit time and compared to the anticipated OEL of 160 g/m^3 TC to verify the validity of using the "accepted" design dilution factor of 0.06 m^3/s/kW of nominal power at the point of application.

Figure 16 shows the derived fresh air dilution flowrates. Figure 17 shows the same results normalised for the rated power of the test engine, 137 kW, in order to yield results comparable to the above design dilution factor (indicated by a purple line).

In all cases, it is significant to note the impact that engine age and poor maintenance may have on the quality of the exhaust stream and the impact these factors would have on fresh air demand and related ventilation system capital and operational costs.

These results also show the benefit of using particulate filters in reducing the required fresh air dilution quantities. Of concern in these findings is the apparent inadequacy of using a dilution factor of 0.06 m^3/s/kW of nominal power at the point of application without due consideration of the vehicle, fuel and exhaust after-treatment provided. This might affect the ability of older diesel engine technology and fuels to meet the proposed DPM OEL.

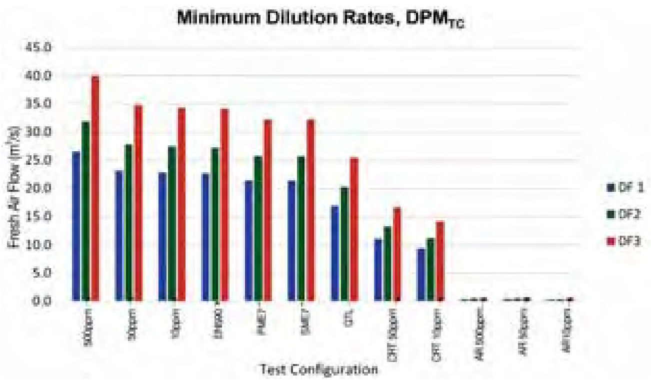

Figure 16. *Fresh air dilution factors for emitted TPM*

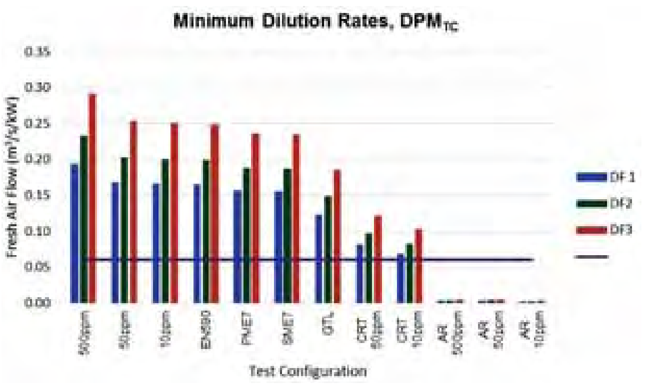

Figure 17. *Normalised fresh air dilution factors for emitted TPM*

In summary, dilution factors presented in this section show that for the Tier 1 engine tested, based on the specific operational cycle simulated and fuels used, adequate gas dilution may be achieved reasonably easily, particularly where cleaner burning fuels are used. However, results also show that the design dilution rate traditionally applied to diesel equipment is insufficient to ensure adherence to the proposed particulate matter OEL under these conditions.

These results further indicate that:

- The use of low sulphur fuels promotes cleaner exhaust both in terms of gases and particulates.
- The use of low sulphur fuels allows the use of catalysts in exhaust after-treatment systems that in turn reduce exhaust gas concentration.
- The concentration of emissions from an engine without a particulate filter requires high levels of fresh air dilution and precludes the reuse of air.
- The introduction of particulate filtration systems is essential in meeting the proposed DPM OELs.
- Engine deterioration, due to age and poor maintenance impact significantly on the applicable fresh air dilution rates.
- Reuse of air between sections may only be possible if adequate fresh air dilution is applied - best results being achieved by the use of low sulphur fuels and adequate exhaust filtration.
- Although gas emissions require low fresh air dilution rates, the continual operation of equip-ment in main intakes may result in higher gas and particulate contamination at section entries that would have to be accounted in ensuring adequate air quality in the section.

Although the dilution factors indicated in Figures 16 and 17 are deemed to be achievable using appropriate particulate filtration, it must be remembered that, apart from the capital and operational cost of introducing such technology, the retrofitting of CRT and AR or equivalent particulate filters in existing equipment, specifically in the extra low profile (XLP) vehicles used in narrow reef mines may not be practically possible. A different solution may be necessary to ensure that such existing equipment will comply with proposed diesel exhaust particulate OELs.

It must be clear that these results are indicative and applicable to the type of engine and loading cycle used in the bench tests. Different engine technology or different loading cycles are likely to yield different results and demands on the mine's ventilation system.

In addition, the application of very low fresh air dilution rates where diesel equipment is operated in practice, has to be managed in view of the resulting dry-bulb and wet-bulb temperatures and need to reuse such air further in the mine.

This indicates the need for careful and consistent assessment of diesel fleet performance based on regular, repeatable and representative tests performed on site. Possible consideration should be made in the use of emission based maintenance routines that may be used to “fingerprint” emissions from each vehicle over time and the data used to improve the effectiveness of selected ventilation strategies and assigned dilution quantities.

CONCLUSIONS

After evaluating the effectiveness of seven fuels and two retrofitted diesel particulate filters to reduce diesel particulate matter emissions in a Tier 1 certified Deutz BF6M1013 engine that operates in an underground mine, the following conclusions can be drawn:

The fuel evaluations revealed that switching a mine from 500 ppm diesel to an ultra-low sulphur diesel (50 ppm or 10 ppm) reduced particulate matter emissions by approximately 10%. Adding 7% biodiesel (SME or PME) to ultra-low sulphur diesel reduced particulate matter emissions by a further 5%. GTL diesel offered the biggest DPM reduction of 28.4% from 500 ppm diesel levels.

GTL diesel upgraded the emission rating of the engine from Tier 1 to a partial Tier 3 rating (excluding nitrogen oxides emissions, which remained at Tier 1 despite a 17.9% reduction).

Lowering fuel sulphur from 500 ppm to 50 ppm reduced SO_2 emissions by 81.4%. Lowering fuel sulphur further down to 10 ppm, or less, effectively halved the SO_2 emissions of the 50 ppm diesel.

The exhaust after-treatment evaluation showed that the partial-flow SMF-CRT, when tested with 50 ppm diesel, achieved a particulate matter emissions reduction of 55.7% from the 500 ppm diesel base case (no after-treatment). 10 ppm diesel further reduced particulate matter emissions to 62.2% below the 500 ppm diesel base case; this represented a 14.7% reduction from the 50 ppm result. The SMF-CRT reduced carbon monoxide emissions by over 85%, but significantly increased nitrogen dioxide emissions.

The SMF-CRT upgraded the emission rating of the engine from Tier 1 to a partial Tier 3 rating (excluding nitrogen oxides emissions, which remained at Tier 1 despite around a 10% reduction).

The wall-flow SMF-AR reduced DPM emissions for all fuels (500 ppm, 50 ppm, and 10 ppm) by more than 98% from the 500 ppm diesel base case (no after-treatment). This system increased carbon monoxide emissions for all fuels (500 ppm, 50 ppm, and 10 ppm) by approximately 20% from the 500 ppm base case. NO_2 emissions were effectively eliminated - not NO emissions with all fuels tested, when compared to operating the engine without after-treatment on 500 ppm diesel.

The SMF-AR upgraded the emission rating of the engine from Tier 1 to a partial Tier 4 rating (excluding nitrogen oxides emissions, which remained at Tier 1).

The use of low sulphur fuels and particulate filters in the exhaust train will enable the use of a lower specification diesel engine in mines without the introduction of excessively high air quantities. The ability of adapting existing equipment and up-skilling technical personnel in the installation, use and maintenance of such equipment is key in achieving these results.

Considerable reductions in air quantities for sections where diesel-powered equipment is operated are dependent on the ability to limit pollutant levels as well as air temperature and humidity in the reject air stream - particularly where these are to be reused elsewhere in the mine.

RECOMMENDATIONS

Based on the findings in this report, the following are recommended:

Currently available ultra-low sulphur diesel should be considered to immediately and significantly reduce emissions in underground mines that are currently being supplied with 500 ppm diesel. This can be further improved in conjunction with retrofitted after-treatment technologies.

Customised fuel formulations that contain bio-diesel and/or GTL diesel are avenues available to achieve even greater diesel particulate matter emission reductions, however commercial supply of large volumes is limited with these fuels, and fuel handling or blending requirements become onerous. It is recommended that a limited follow-up study is executed, where organic, metal-free combustion improver additives (original commercial additives only) are added to a commercially available fuel (50 ppm or 10 ppm diesel) to assess the potential of this technology. The optimised fuel could be delivered to underground mining customers with the additive package preblended.

The SMF-CRT represents a relatively low-cost, compact, bolt-on solution which offers significant diesel particulate matter, carbon monoxide, and total unburned hydrocarbon reductions. It is recommended to evaluate its performance in the test cell using an 8 hour shift simulation to verify if the exhaust temperatures are indeed high enough to sustain continuous soot oxidation on the filter material, and therefore prevent filter blockage. Service life endurance tests could also be considered.

Assess a passively regenerating DPF system that does not increase NO_2 above engine-out levels (such as a CRT combined with a NO_2 decomposition catalyst).

Consider the introduction of regular and consistent site-based engine emission testing to characterise the performance of and emission from all vehicles. This data may be used to assess the effectiveness of maintenance procedures and to optimise the allocation of fresh air while ensuring adequate air quality of all operational sites.

ACKNOWLEDGEMENTS

Acknowledgements below are given in no particular order.

The authors gratefully acknowledge Bathopele Mine for hosting me for two days to carry out the LHD duty cycle recording. This recording was pivotal to reproduce realistic engine operation in the test cell, and therefore generate relevant engine exhaust emission results.

Anglo American's engineering team is also gratefully acknowledged for their guidance and facilitation roles throughout the project, as well as for arranging the fuel analysis at Intertek.

Appreciation is also extended to Deutz Diesel-power for supplying a run-in test engine and the two after-treatment systems. Their support in commissioning the engine, supplying CAN protocol information, assistance at Bathopele, and after-treatment commissioning was invaluable.

The supply of the SME and PME biodiesel from FalconMere is very much appreciated.

The diesel particulate filter supplier is gratefully acknowledged for the technical information shared with the author around their two after-treatment systems.

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In general, the success of this extensive investigation into the reduction of emissions from diesel-powered equipment in underground mines was enabled by an industry wide collaboration, and would not have been possible without the professional, open, and committed interactions within the project team.

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Peer reviewed for Journal publication

XLP/ULP On-Reef Mechanised Mining Method by Ventilation on Demand as a concept

J. Venter[1]*, M.B. Diedericks*[2]
[1]*BBE Consulting,* [2]*Manager: Ventilation and Refrigeration, Anglo American Platinum*

ABSTRACT

The application of a ventilation on demand system (VoD) as a concept has shown that a savings of R456 million can be achieved in operating cost. This could have a significant impact on the NPV and IRR of the project, especially in the current economic environment. The impact of the fit for purpose ventilation doors and fans will play a role in determining the ultimate success of the application of VoD in the XLP/ULP layout.

This paper discusses the overall design, cost reduction and challenges of such a VoD system to support the Extra Low Profile (XLP) and Ultra Low Profile (ULP) on-reef mechanised mining methods.

A number of ventilation challenges are associated with Mechanised Mining. Ventilation requirements are significantly increased to ensure exposure to harmful gases, vapours and particulates are controlled to acceptable limits. The application of VoD will ensure that ventilation requirements are maintained by directing the ventilation flow to the areas where mechanised machines are operating compared to a continuous supply of ventilation to all mining areas. This will result in a significant reduction in the overall ventilation requirements and associated cost.

Keywords: *Ventilation on demand, mechanised mining, ventilation cost, ventilation requirements.*

INTRODUCTION

Historically, conventional mining methods were applied throughout the platinum industry with a very small percentage of operations utilising mechanised mining methods. It can be argued that the reason for conventional mining methods is mainly due to the narrow tabular orebody and the unavailability of technology to mine such an orebody.

The mining industry, in conjunction with equipment suppliers, developed a suite of mechanised mining equipment that can exploit such a narrow ore body effectively and at a competitive cost. This resulted in a major shift in the mine extraction strategy (MES) of a number of mining houses to the extent that a number of new operations are currently planned with extra low profile mechanised mining equipment. A number of ventilation challenges are associated with mechanised mining. Ventilation requirements are significantly increased to ensure that exposure to harmful gasses, vapours and particulates is controlled to acceptable limits resulting in an increase in ventilation infrastructure, capital and operating cost.

The application of ventilation on demand (VoD) will safeguard that ventilation requirements are sustained by directing the ventilation flow to the areas where mechanised machines are operating compared to a continuous supply of ventilation to all mining areas. This paper describes the overall design, cost reduction and challenges of such a VoD system to support the Extra Low and Ultra Low Profile mechanised mining methods.

EXTRA LOW AND ULTRA LOW PROFILE (ULP/XLP) MINING METHODOLOGY

Typically access to the orebody is by means of an on-reef decline system at an apparent dip of 9°, strike belt drive and a transport strike drive. Depending on the mine design, either a conveyor belt or trucks can be used to transport ore out of the mine. Typically, stope raise lines are developed 215 m apart, with raise and winze development taking place simultaneously.

Depending on the backlength, the stoping layout consists of seven panels on either side of the raise line. The panels are 25 m long and include a 5 m wide advance strike drive (ASD) at the bottom of each panel. Stoping configuration is based on a standard conventional breast mining layout. Ledging starts off with developing the ASDs 12 m in from the raise. This is followed by ledging 4 m in on both sides utilising low profile (LP) mining equipment. A 5 m wide ramp is established at the top and bottom of the panel to establish access for the XLP mining equipment. Figure 1 shows the typical layout of the XLP mining method.

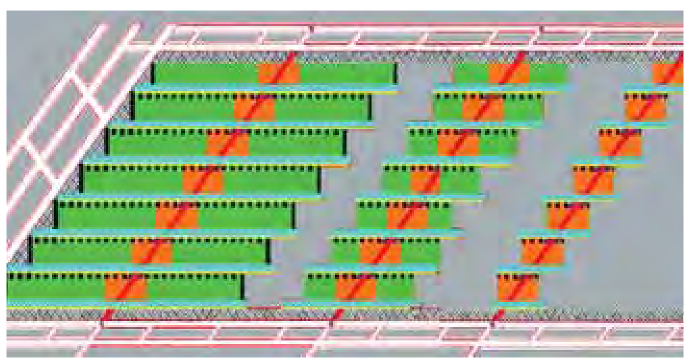

Figure 1. *Typical XLP/ULP Mining Layout*

VENTILATION DESIGN CRITERIA AND METHODOLOGY

The ventilation requirements for mechanised diesel equipment are determined by considering a number of factors and design rules. Previous work done in the industry indicates that a ventilation requirement of 0.06 m^3/s to 0.12 m^3/s per rated engine power is required to effectively dilute exhaust emissions and diesel particulate matter (DPM) to acceptable limits. The ventilation requirement factor is dependent on the quality of diesel fuel used and the emission control level of the diesel engine being used. As

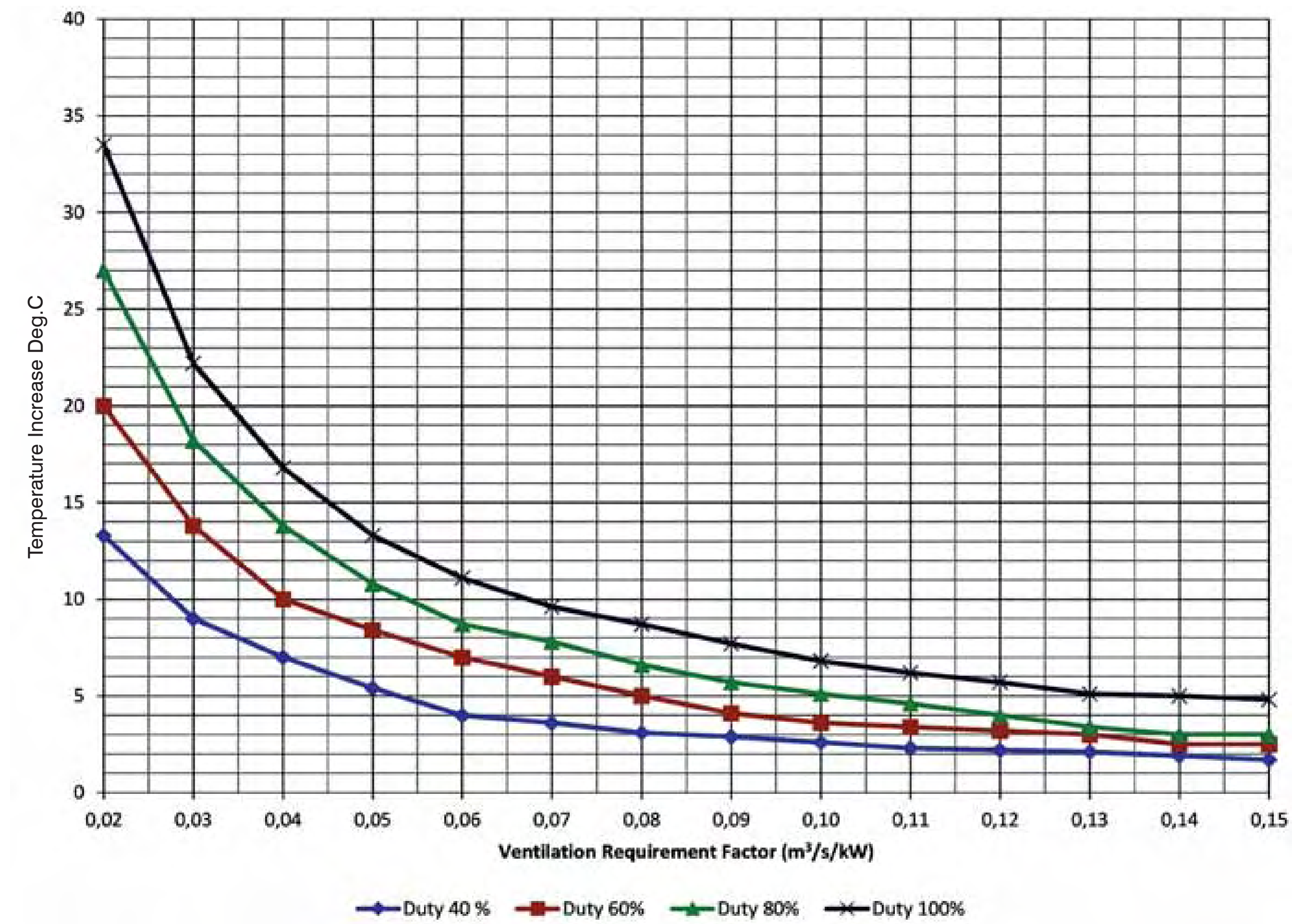

Figure 2. *Ventilation Requirement Factor to compensate for temperature increase (Roman and Nundlall, 2014)*

mining depths increases the heat production will increase and the ventilation requirement factor will have to be increased to ensure sufficient air cooling power up to the point where refrigeration is introduced. Figure 2 indicates the required increase in the ventilation factor ($m^3/s/kW$) to compensate for increase in temperature due to the operation of diesel powered vehicles.

Typical diesel fleet

The highest heat load contributors to the mining environment are the LHD and XLP dozer as they continuously operate during the course of the shift. The ventilation requirements are indicated in Table 1. The heat load added by the other XLP equipment is seen as negligible.

Table 1. *Ventilation requirements for the high heat load XLP mining equipment*

Description	Rated Engine Power (kW)	Ventilation Factor ($m^3/s/kW$)	Volume Required at point of application (m^3/s)
8ton LHD	140	0.06	8.4
XLP Dozer	60	0.06	3.6

VENTILATION ON DEMAND OVERVIEW

VoD is a well-established method used in mechanised mining layouts to reduce the ventilation requirements, associated infrastructure and main fan energy consumption. In South Africa, VoD forms part of energy saving initiatives but are not very well practiced in the local industry. Some of the reasons why VoD is not embraced in the local industry are:

- Complexity;
- Historical low cost of electricity;
- The need not identified due to conventional mining methods.

On a micro or localised form, VoD is mainly used in development ends. The development end auxiliary fan delivery volume is controlled by means of a variable speed electrical motor (VSD). The principal of operation is based on speeding up the fan to increase the delivery volume when a diesel vehicle enters the development end and reducing the fan speed to reduce the delivery volume when the vehicle exits the end. Looking at a macro scale, VoD can be implemented on main fans to increase or decrease the fan speed and associated ventilation volume as the mining load varies from day to day.

Ventilation on Demand - XLP Mining Method

The VoD concept as proposed for the XLP mining method is based on supplying the correct volume of ventilation to dilute diesel exhaust fumes and associated heat when the diesel vehicles access the stope panels through the advanced strike drive (ASD) to load the blasted ore. The remaining ASDs will not be supplied with any ventilation. The control of ventilation supply will be done with automated ventilation doors and fans installed in each of the ASDs. When the LHD enters an ASD the ventilation door will open, allowing access, the door will close and the fan will be switched on to supply the required ventilation flow.

VENTILATION REQUIREMENT COMPARISON FOR A TYPICAL XLP MINING STOPE BLOCK

Traditional Ventilation Methods ("Flood Ventilate")

A stoping block consists of fourteen mining panels with fourteen advanced strike drives. A mechanised diesel LHD accesses the mining panel through the ASD, loading the blasted ore cleaned by the XLP dozer. By applying the ventilation requirement factor of 0.06 m^3/s to the point of application, the 136 kW LHD, requires 8.4 m^3/s at the loading point. Including leakage of 20% due to inefficient ventilation seals, a total of 10 m^3/s of ventilation flow is required for each of the fourteen ASDs. In addition, 10 m^3/s of ventilation flow is required for the center raise line used by the LHD to transport the loaded ore to the strike conveyor belt. A ventilation supply of 150 m^3/s is required for each of the stoping blocks when applying traditional ventilation methods. In-take air will be supplied from both the belt and strike drives; with a combined excavation size of 32.5 m^2 the required volume can be supplied at 4.6 m/s. The maximum quantity of air that can be supplied on a half level is 163 m^3/s at a velocity of 5 m/s (maximum velocity in conveyor belt). This could restrict mining to a single connection on each half level. Table 2 shows a summary of the ventilation requirements per stope block for the traditional ventilation method for a mechanised mine.

Table 2. *Volume requirement for the conventional ventilation method*

Description	Requirement
Air flow quantity for each ASD	10 m^3/s
Number of ASDs	14
Air flow quantity for raise line (center gully)	10 m^3/s
Total air flow quantity	150 m^3/s (1)

(1) Compared to a conventional breast mining method, at the same depth a typical volume of 15 m^3/s will be required.

Ventilation of Demand

Irrespective whether a LHD is loading in any of the ASDs a fixed volume of ventilation will be required to flow through the stoping faces to remove blasting fumes, dust and heat to ensure other mining activities can be performed safely. This ventilation supply will typically be supplied through the bottom two ASDs and will be reused through the fourteen stope faces. Typically the ventilation requirement to maintain the required stope face ventilation flow is based on the mining height, strike control distances and the required stope face velocity. See figure 3 for a typical Ventilation on demand layout. It should be noted that for the XLP layout the volume required for the bottom two ASDs to dilute fumes and heat generated by the LHD is higher than the volume required to maintain the minimum face velocity. For this reason the higher volume will be used to determine the overall air requirements.

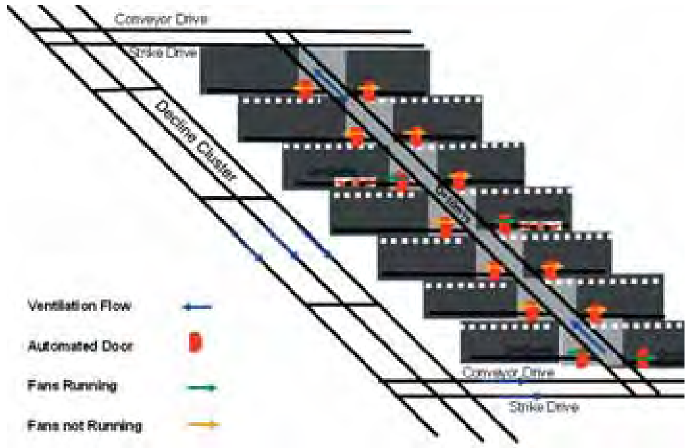

Figure 3*. Ventilation on Demand - Principle of Operation*

VENTILATION REQUIREMENTS APPLYING VENTILATION OF DEMAND

Ventilation and heat load simulation

Ventilation and heat load simulations were conducted using Vuma-3D network. The simulation was done on a typical XLP stope block. See Figures 4 and 5.

The purpose of the simulation is listed below:

- Determine the airflow quantity required to maintain an average wet-bulb temperature of 29.0°C;
- Verify the fan specification for the VoD fans.

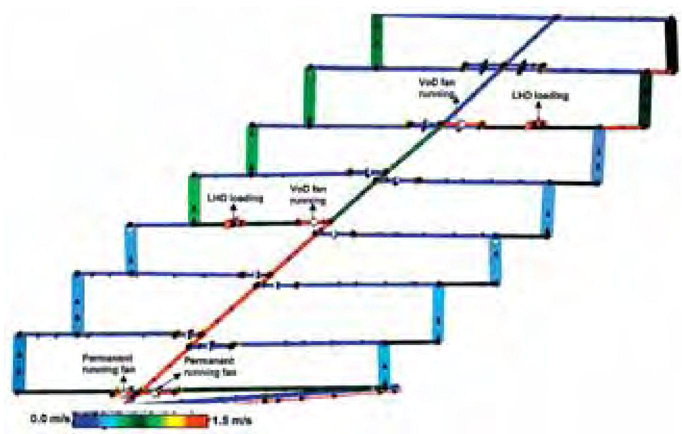

Figure 4. *VoD arrangements for typical XLP block*

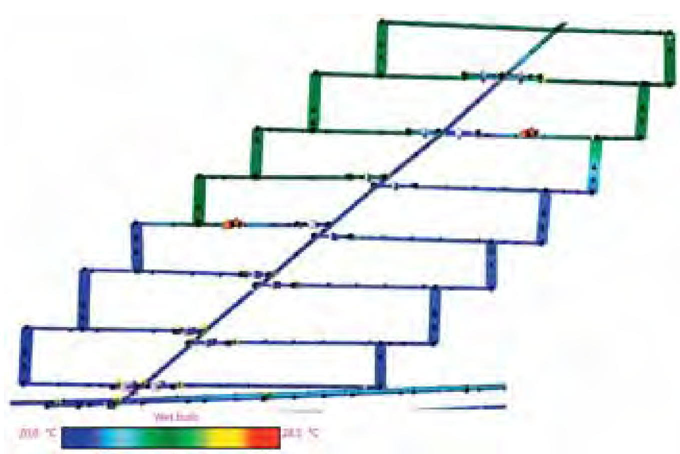

Figure 5. *Temperature distribution through the XLP stope block*

Stope Connections

Minimum face velocity required = 0.5 m/s

Face quantity required to maintain face velocity

[Stoping width (1.2 m) x velocity (0.5 m/s) x curtain distance (12 m)]

+ inter stope leakage (20 %) = 8.6 m^3/s

Double sided mining =17.2 m^3/s

For the XLP layout, it is required for a LHD to enter and load in each ASD. To ensure a sufficient quantity of air is available to dilute exhaust fumes and heat generated, the following will apply:

Minimum quantity required for LHDs entering an ASD

[Rated LHD (140 kW) x diesel dilution factor (0.06 m^3/s/kW)]

+ inter stope leakage (20 %) = 10.0 m^3/s

The quantity required for the bottom two ASDs to dilute fumes and heat generated by the LHD is higher than the quantity required to maintain the minimum face velocity. For this reason, the higher quantity will be used to determine the overall air requirements for the stope connection.

For double sided mining = 20 m^3/s

The remaining 12 ASDs will be ventilated using VoD

Quantity required for LHD (VoD)

Number of LHDs per stope = 2

Total quantity for LHDs (VoD) = 20 m^3/s

Quantity required for center gully = 10 m^3/s

Total quantity required =50 m^3/s

Quantity Required for In-Series Stopes

Ventilation supply will be re-used with a reduced quantity of fresh air supplied to the in-series stope connection to ensure the exhaust fumes and heat produced from the bottom stope line is effectively reduced. The reduced quantity will be based on the LHDs working in the in-series stope line. VoD principals will apply.

Quantity from bottom stope = 50 m^3/s

Quantity required for LHD (VoD)

Number of LHDs per Stope = 2

Total quantity for LHDs (VoD) = 20 m^3/s

Total quantity required = 20 m^3/s

Ledging Connection

Minimum face velocity required = 0.5 m/s

Face quantity required to maintain face velocity

(Stoping width (1.2 m) x velocity (0.5 m/s) x curtain distance (12 m)) + inter stope leakage (20 %) = 8.6 m^3/s

Double sided mining =17.2 m^3/s

Vamping Connection

Minimum face velocity required = 0.5 m/s

Face quantity required to maintain face velocity

[Stoping width (1.2 m) x velocity (0.5 m/s) x curtain distance (12 m)]

+ inter stope leakage (20 %) = 8.6 m3/s

Double sided mining =17.2 m^3

For the XLP layout it is required for a LHD to enter and load in each ASD. To ensure a sufficient quantity of air is made available to dilute exhaust fumes and heat generated the following will apply:

Minimum quantity required for LHDs entering an ASD

(Rated LHD (140 kW) x diesel dilution factor (0.06 m^3/s/kW)

+ inter stope leakage (20 %) = 10 m^3/s

The quantity required for the bottom two ASDs to dilute fumes and heat generated by the LHD is higher than the quantity required to maintain the minimum face velocity. For this reason, the higher quantity will be used to determine the overall air requirements for the stope connection.

For double sided mining = 20 m^3/s

The remaining 12 ASD will be ventilated using VoD

Quantity required for LHD (VoD)

Number of LHDs per stope = 1

Total quantity for LHDs (VoD) = 10 m^3/s

Quantity required for center gully = 10 m^3/s

Total quantity required = 40 m^3/s

Table 3 shows a comparison between traditional mechanised ventilation methods and ventilation of demand for a typical stope block. It can be seen that the air flow quantity for the VoD is 100 m^3/s less compared to traditional ventilation method.

Table 3. *Comparison between conventional ventilation method and VoD*

Description	Traditional ventilation method	Ventilation on Demand
Air flow quantity for each ASD	10 m^3/s	10 m^3/s
Number of ASDs	14	14
Air flow quantity for bottom ASDs	-	20 m^3/s
VoD (2 x LHDs)	-	20 m^3s
Air flow quantity for raise line (center gully)	10 m^3/s	10 m^3/s
Total air flow quantity	150 m^3/s	50 m^3/s
Reduction in airflow quantity	100 m^3/s or 67%	

METHOD COMPARISON - CONVENTIONAL VENTILATION AND VENTILATION ON DEMAND

To illustrate the potential advantages of the VoD system it should be compared against traditional ventilation methods. For this purpose a typical narrow reef platinum mine, mining from an on-reef three barrel decline system, developed from surface to a depth of 500 m below surface will be used. The combined ventilation intake capacity of the decline is 264 m^3/s at a velocity of 5.0 m/s. A production rate of 200 kilo tons per month from six half levels. A typical half level will consist of vamping, stoping and ledging connections. Ventilation will be reused over three stoping back lengths on each side of the decline cluster. The bulk of the ventilation supply will be directed to the bottom half levels.
A reduced airflow quantity will be supplied to the remaining half

levels to dilute diesel fumes and heat produced from mining operations. Tables 4 and 5 indicate the ventilation requirements and infrastructure when comparing traditional ventilation methods and VoD methods.

FINANCIAL IMPACT OF VENTILATION ON DEMAND

Savings associated with VoD can be significantly reduced in two areas:

• Ventilation Infrastructure (CAPEX);

• Operating Cost (OPEX).

Table 4. *Ventilation Requirements - VoD compared to traditional ventilation methods*

	Traditional ventilation method		Ventilation on Demand	
	Bottom Half Level (m^3/s)	In-Series Half Level (m^3/s)	Bottom Half Level (m^3/s)	In-Series Half Level (m^3/s)
Vamping connection	150	10	40	10
Stoping connection	150	20	50	20
Ledging connection	20	20	25	25
Ventilation flow	320	50	115	55
Number of half levels	2	4	2	4
Sub total	640	200	230	220
Total ventilation	840		450	

Table 5. *Ventilation Infrastructure - VoD compared to traditional ventilation methods*

	Traditional ventilation method		Ventilation on Demand	
Infrastructure Required	Diam. (m)	Qty.	Diam. (m)	Qty.
Intake Ventilation Shaft(s)	5.5	2	4.6	1
Exhaust Ventilation) Shaft(s)	5.5	2	4.0	2
Main Fans	200 m^3/s @ 3.5 kPa	4	150 m^3/s @ 3.5 kPa	3

VENTILATION INFRASTRUCTURE

Ventilation infrastructure is significantly reduced when applying VoD to the XLP Mechanised Mining Method. The capital savings associated with this method are mainly in ventilation shafts and main ventilation fans. Additional equipment is however required for the VoD control system in the form of automated ventilation doors and fans for each ASD. Table 6 indicates the ventilation capital cost for a typical mine as described earlier in the paper.

Table 6. *Capital Cost*

Infrastructure	Traditional ventilation method	Ventilation on demand
Ventilation Shafts	R20mil - 2 by 5.5 m dia. intake shafts - 2 by 5.5 m diameter exhaust shafts	R10mil - 1 by 4.6 m dia. intake shafts - 2 by 4.0 m diameter exhaust shafts
Main Fans	R70mil 4 by 200 m^3/s @ 4.0 kPa	R48mil 3 by 150 m^3/s @ 4.0 kPa
Ventilation Doors (VoD)	Nil	R14.5mil 112 by Automated ventilation doors
Fans (VoD)	Nil	R9mil 112 by VoD in-stope fans
Total	R90mil	R81.5mil

OPERATING COST

With a reduction in airflow quantity of more than 40% compared to the traditional ventilation method, the potential cost saving of R456 million can be realised over a period of 20 years. The additional operating cost of the ASD fans was included in the financial evaluation (calculated difference from Table 7). Overall maintenance cost of main and auxiliary fans were not included as part of the operating cost. Table 7 shows the input parameters used to calculate operating cost.

Table 7. *Operating cost*

Operating Cost	Traditional Ventilation Methods	Ventilation on Demand
Electrical Cost	R 0.85/kWh	
Life of Mine	20 Years	
Discount Rate	11.5%	
Main Fans - Input Power Cost (annual)	R 32 166 720	R 24 426 603
VOD Fans - Input Power Cost (annual)	Nil	R 100 246
Operating Cost (Nominal)	R1 895 105 581	R1 439 095 801

DISCUSSION

The use of VoD for XLP mechanised mining demonstrates financial viability when compared to traditional ventilation methods. A number of challenges associated with VoD have been identified. These challenges include:

• Ventilation Doors selection;

• Fan Selection.

Ventilation Doors

Ventilation doors play a very important role in the principal of operation. Doors should be robust, open and close at an acceptable speed to prevent possible production losses. In addition, doors should be low cost and easy to maintain. Alternative methods to control the ventilation flow are being investigated and will form part of the concept testing phase.

Auxiliary Fan Selection

Ventilation simulations indicated that the typical design specifications for these fans are in the order of 12 m^3/s @ 200Pa. This is considered as a low pressure - medium flow fan and is not an "off-the-shelf" fan and will require special design and manufacturing. A reputable fan manufacturer is in the process of designing a fan to this specification for testing purposes.

CONCLUSION

In conclusion, it can be seen that the heat load added by diesel machinery is a significant contributor to the total heat load at shallow depths and therefore the traditional method of ventilating becomes uneconomical as the air requirements are high due the need to dilute the gases and particulates from diesel machinery. VoD results in a reduction in airflow quantity of more than 40% when compared to the traditional method of ventilating mechanised mines.

The application of a VoD system is essential to allow for project success as it is shown that a savings of R465 million in total ownership cost can be achieved and this will have a significant impact on the NPV and IRR of the project especially during the current economic environment mining companies find themselves. The impact of the fit-for-purpose ventilation doors and auxiliary fans will play a role in determining the success of the application of VoD in the XLP/ULP layout.

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Farewell Dirk van Greuning

A ceremony was recently held to bid farewell to Dirk van Greuming. Marthinus van der Bank presented him with a gift in thanks for all his years of service to Sibanye Gold.

Mr. Dirk van Greuning started his mining career on 1 January 1975 at Kloof Gold mine as a mining learner official, and switched to ventilation in November of the same year.

He was transferred to East Driefontein mine in 1980 and was promoted to Section Ventilation Officer in 1981. He joined Beatrix mine in 1983 and was transferred to St. Helena mine in 1984 and again was moved to Oryx mine in 1988. He was promoted to Ventilation Superintendent in July 1992 and transferred to Kinross mine in 1994. He was transferred back to Oryx in 1996 and assumed responsibility for both Beatrix and Oryx mines, as Manager (Ventilation Services), in March 2000 to March 2013.

Dirk is currently the Group Occupational Hygiene Manager at Sibanye Gold Corporate office.

Dirk has a total of 42 years active service with the MVSSA, he is also a past President of the society and has served for 17 years on Council.

He is a well-respected mine ventilation professional and has been a mentor for many others over the years.

MVSSA CONFERENCE 2016

The increasing relevance of the Mine Ventilation Profession in a highly regulated and cost constrained environment

Held from 1 - 2 September at Emperor's Palace Ekurhuleni

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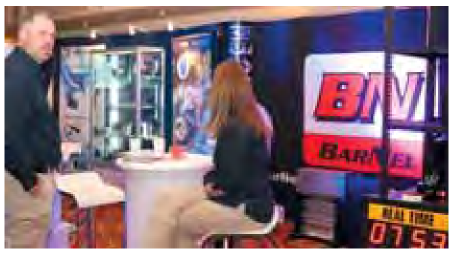

Bar Nel

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Schauenburg

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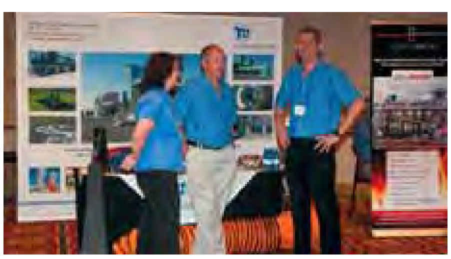
AMS Haden

MechCal

Afrox

Terramin



TLT Actom

ABC

CDC - Cleanair

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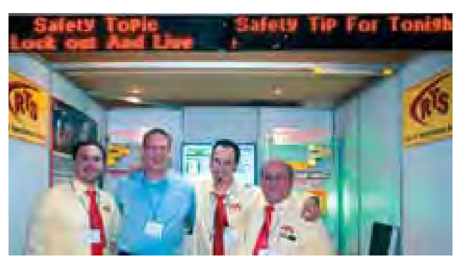
Booyco Electronics



RTS

Presenters and presentations


The conference was opened by the MVSSA President, Mr N Roman. Four sessions were held on day one. The keynote speaker was Prof C Musingwini, President of the SAIMM. Session 1 was chaired by Mr F von Glehn; Session 2 by Dr J Kielblock; Session 3 by Prof J du Plessis and Session 4 by Mr F von Glehn.

Day 2, Session 1 was chaired by Mr M Biffi and Session 2 by Mr H Moorcroft.






















Integrated monitoring to avoid incidents and safety stoppages

More frequent government-ordered safety stoppages on mines - which demand a halt to a mine's entire operation - highlight the need for a system that detects potential collisions underground and alerts personnel of dangerous situations, according to Booyco Electronics continuous improvement manager, Jaco du Plessis.

The Chamber of Mines recently reported that South African platinum producers had experienced three times as many 'Section 54' stoppages by the Department of Mineral Resources in 2016 than previous years; the cost of safety stoppages for the industry as a whole were estimated at R4,8 billion in 2015, up from R2,6 billion in 2012, the report said.

"The PDS is designed to allow for intervention where a potentially dangerous situation exists between a pedestrian and a machine," says Du Plessis. "Consisting of a sensing device that detects the presence of an object in a working area, the system can provide an audible and visual alarm to both the equipment operator and pedestrians as they enter danger zones."

Warning zones can be specified to suit the requirements of specific mine areas, and standardised to a particular type of equipment.

"PDS technology also makes it possible to locate pedestrians and vehicles underground, which enhances production efficiencies and facilitates the locating of people and machinery in an emergency," Du Plessis explains. "Data from the system can be analysed and patterns identified, so that unsafe behaviour can be detected and safety interventions initiated."

He says the PDS was developed as part of the Booyco Electronics Asset Management System (BEAMS) that provided underground and surface mining operationswith a web-based application and robust database to optimise mine safety and ensure compliance to relevant legislated requirements.

"A comprehensive asset management system should allow data to be accessed at any point in time," he says. "This access to real-time information enables operations to make better-informed decisions and avoid potentially harmful incidents. Critically, this information must also be available after an event, as it can be invaluable in tracingand identifyingpossibleroot causes."

He also highlights the importance of asset monitoring in optimising mine operations and increasing productivity.

"Essentially, BEAMS is a central information hub that links the company's proximity detection hardware products and monitoring devices, capturing and recording data together," he says. "This provides a reliable single source of information that can be leveraged for greater insight into all aspects of the operation."

Contact: Anton Lourens
Booyco Electronics (Pty) Ltd
Tel : 0861 BOOYCO (266926) / Email : anton@booyco-electronics.co.za / www.booyco-electronics.co.za

Call for abstracts

The Council of the MVSSA has always recognized that the Profession needs to keep pace with the changing mining environment. Right now the legislative imperatives draw us into a direction where measurement seems to be more important than finding engineered solutions to problems, we are experiencing skills shortages at all levels, ventilation departments are being staffed to focus more on the measurement needs than on the bigger picture, and the qualifications are undergoing major changes and upgrades. There are a number of recent technological developments that could assist the profession in gathering data more efficiently and making better use of them in mining initiatives that are becoming more technologically advanced and sophisticated. If we do not embrace these developments, the South African Ventilation Profession could be overtaken and eventually forced into reactive actions.

The aim of the 2017 conference is to look at the future in terms of technological advancements that can be practically incorporated in the way we do things, and to plot a path on how this may be achieved. The objective is to plant seeds in education, training, technological research and advancement, application of these in a modern mining environment and give a new direction for future mine ventilation professionals. The focus for this includes suppliers of such technology, academia, Skills Development Providers (SDP), researchers and operations.

A perception has been created (rightly or wrongly) that delegates attend the annual conferences to learn only whereas they should come prepared to challenge and share. The 2017 Conference aims to dispel this perception and make sure that the Profession stays on the right path to assure its and the mining industry's future.

The conference will be held on 27 and 28 July 2017 at Emperor's Palace, in Ekurhuleni, Gauteng. Attendees will be awarded CPD points. Exhibitors will showcase their products and there will be many opportunities to network and meet colleagues to discuss the issues further.

Abstracts are being sought from mine ventilation professionals, members of other professions within the industry, students, academics and suppliers to highlight:

- Technology and the influence of technology on the ventilation fraternity
- Latest technologies that are, or could be, applied in the Profession Energy, Engineering, Occupational Health issues
- Education and Training of Ventilation Professionals (current and planned)
- The view from operations
- Latest research into improving mine ventilation

Please submit abstracts of no longer than 500 words to the MVSSA Secretary at secretary@mvssa.co.za.
On acceptance of abstracts a paper template will be made available.

Submission of abstracts	10 February 2017
Notification of acceptance of abstract	24 February 2017
Submission of completed papers	21 April 2017
Notification of peer review comments	9 June 2017
Final submission of corrected papers	23 June 2017

Papers will be peer-reviewed before acceptance in the conference proceedings. Authors undertake to attend the conference and present their papers.