[¶36-162] The efficiency of Disposable Filter Elements to control worker exposure to diesel particulate matter in underground coal mines

Jennifer M. Hines, Vinod Gopaldasani, Casper J. Badenhorst and Brian Davies

Jennifer M. Hines, BSc, MSc, is a Lecturer in the Occupational Health & Safety Group, School of Health & Society, University of Wollongong, NSW, Australia.

Vinod Gopaldasani, MBBS, MSc, PhD, is a Lecturer and Academic Program Director in the Occupational Health & Safety Group, School of Health & Society, University of Wollongong, NSW, Australia.

Casper J. Badenhorst, BSc, MSc PhD, is an Honorary Fellow in the Occupational Health & Safety Group, School of Health & Society, University of Wollongong, NSW, Australia.

Brian Davies, BSc, PhD, is a Professor in the Occupational Health & Safety Group, School of Health & Society, University of Wollongong, NSW, Australia.

Address for correspondence: Dr Brian Davies, Professor Occupational Health & Safety, School of Health & Society, University of Wollongong, NSW, Australia 2522.

Email: bdavies@uow.edu.au

Tel: +02 42215034

Conflict of interest

The authors of this paper declare no conflict of interest.

Abstract

Disposable Filter Elements (DFEs) are used by the underground coal mining industry to control worker exposure to diesel particulate matter (DPM) emissions from mobile diesel engines. This study investigated the actual in-service filtration efficiency of DFEs when installed for immediate use as is the current practice. Four different DFEs were tested using statutory and in-service methods and the exhaust results analysed for elemental carbon, a surrogate for DPM. Using the statutory test method, two of the four DFEs had a filtration efficiency that was below the industry-accepted six-hour average efficiency of >85% in the first 15 to 30 minutes of testing while one DFE did not reach the required efficiency 45 minutes to one hour into testing. In-service testing of two of the DFEs showed even lower filtration efficiencies of 62% and 69%, respectively. The “lag period” in DFEs reaching >85% filtration efficiency exposes workers to higher than expected levels of DPM, a known carcinogen.

Keywords: Disposable Filter Elements (DFEs); Disposable Diesel Exhaust Filters (DDEF); diesel particulate matter (DPM); diesel emissions.

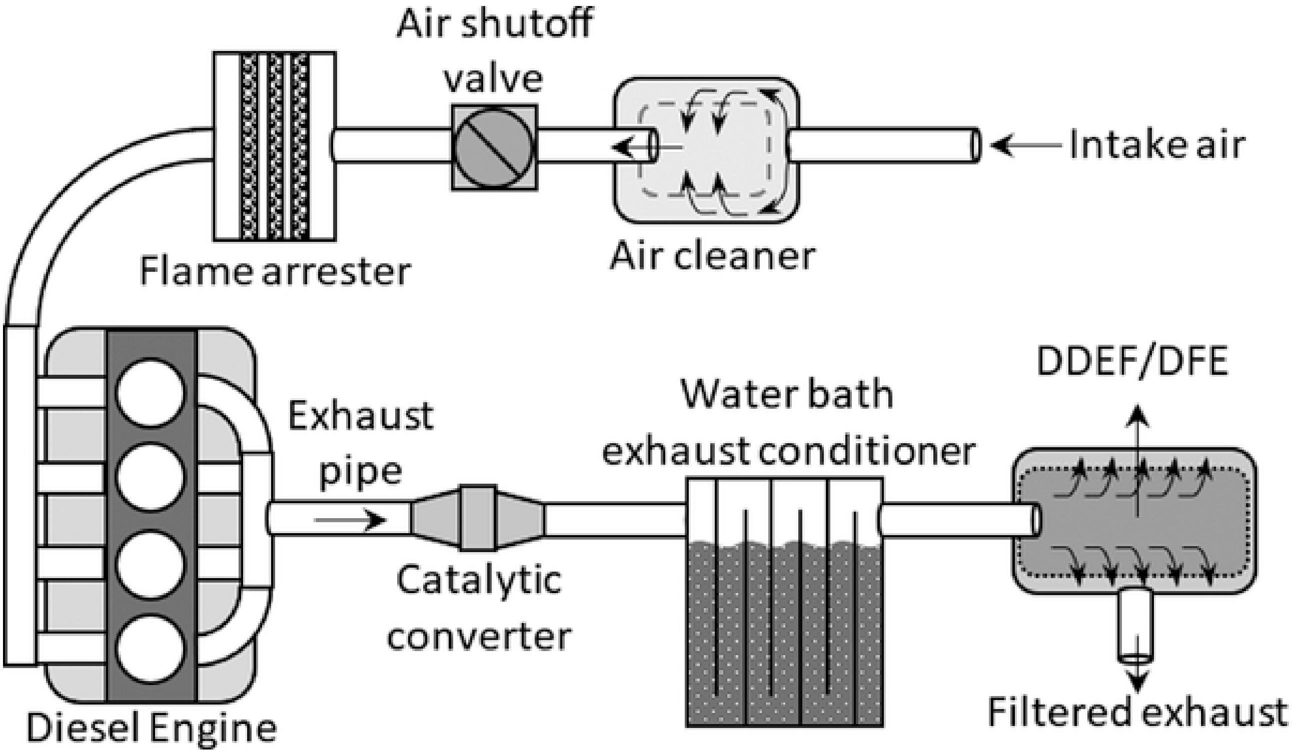
Introduction

Diesel engines are widely used in the mining industry in heavy vehicles due to their power output to transport mined products and materials. The combustion process of diesel fuel in these engines results in emissions of various gases and particulate matter, particularly diesel particulate matter (DPM). Diesel exhaust emissions were declared a human carcinogen by the International Agency for Research on Cancer (IARC) in 2012 (1, 2). Efforts to control diesel exhaust emissions in mines have been ongoing for many years, mainly due to legislative requirements to protect workers exposed to diesel emissions.

The concept of using a filter in the exhaust of diesel vehicles in coal mines to control worker exposure to DPM was first presented by Ambs and Hillman (3) following research at Skyline Mine in Utah, USA. The proposal consisted of using an “over the road” truck air filter element in the exhaust of the vehicle with the filter being replaced at regular intervals, thus leading to the name Disposable Filter Elements (DFEs) or alternately Disposable Diesel Exhaust Filters (DDEFs).

The DFE was inserted into the exhaust stream after the water-filled conditioning tank which is used to suppress sparks and to ensure that the exhaust temperature was reduced to a level where ignition would not occur (below 150°C/300°F). A schematic diagram of the principle of operation of DFE fitted to a diesel engine is depicted in Figure 1.

Figure 1: Schematic of DDEF/DFE operation when fitted to a diesel engine.



The initial low-temperature filter element used by Ambs and Hillman (3) was made of potentially flammable paper (cellulose or synthetic) and had a filtration efficiency (% DPM removed) of 93 ± 7% determined by in-mine studies of worker exposures. Due to the inherent safety requirements in an underground mining environment, the potentially flammable cellulose filter was not deemed suitable to use in diesel vehicles servicing the Australian underground coal mining industry.

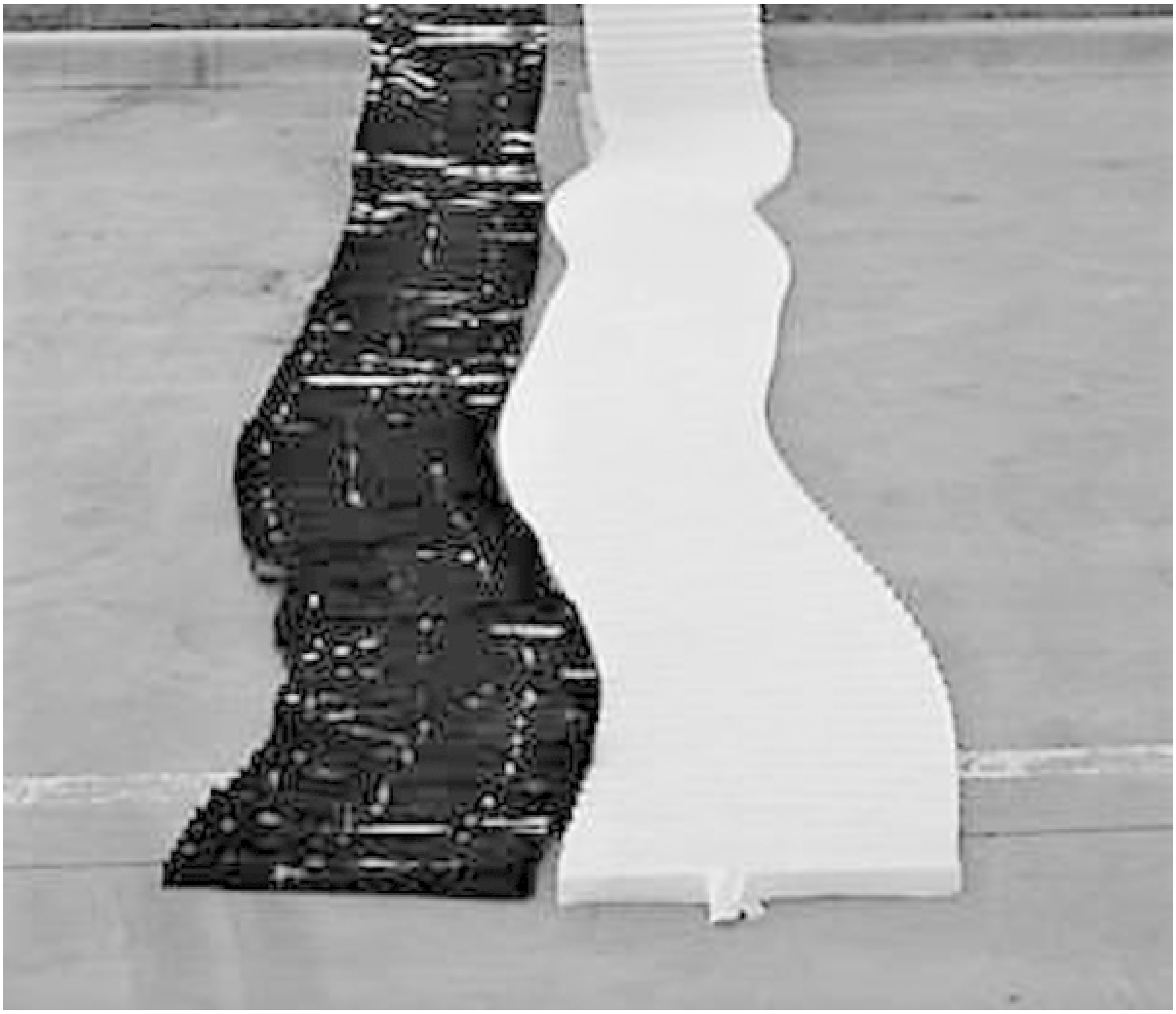
In the early 1990s, a major study in Australia at Tower Colliery (BHP Collieries Pty Ltd) identified DPM as being a potentially significant health risk to their workers (4). This study expanded the development of DFEs as a control strategy for DPM in New South Wales (NSW) underground coal mines. To comply with intrinsic safety requirements, the research team used a non-flammable cellulose filter media with a DPM filtration efficiency of 85%.

The first commercial DFE system was fitted to an operational Load Haul Dump (LHD) diesel vehicle in 1995 (Figure 2) and the application of DFEs was subsequently approved for use and has expanded to many underground coal mines in the Australian underground coal mining industry.

Figure 2: First Load Haul Dump fitted with DFE system.

The almost instant success of this system resulted in all vehicles in BHP Collieries being retrofitted over subsequent years with a lowering of worker exposure to DPM measured as elemental carbon (EC) from 0.12 to 0.05 mg/m^3 (4). The effectiveness of DFEs in removing DPM from the raw exhaust of a diesel engine used in coal mines is visually demonstrated in Figure 3.

Figure 3: Used (black) and new polypropylene diesel exhaust filter media.



Following the introduction of DFEs by BHP Collieries Pty Ltd, similar systems and alternate suppliers of filters emerged resulting in filters being manufactured in Australia, China and the United States. DFEs are manufactured in different shapes and sizes to fit different mining vehicles. The range of different types of DFEs made of different filter media and sourced from different countries potentially brings into question the maximum filtration efficiency of the various DFEs as more efficient filtration media generally comes at a higher cost. In addition, the current practice in the industry of installing a DFE and immediately putting the heavy-duty vehicle into service also questions the relative protection of workers against diesel emissions, as this practice assumes the DFE is working at its maximum filtration efficiency from the instant of installation on the diesel vehicle. Hence testing of DFEs is now more important than ever especially with regards to certifying filters for use with their rated filtration efficiency from the moment it is installed.

The introduction of statutory and in-service emission testing in Australian mines, especially in NSW through the Mine Design Guide (MDG) 43 Statutory test method (5) and the MDG 29 “in-service” test method (6) has increased the scrutiny of emissions compliance for diesel fleets in underground mining. The use of diesel exhaust filters was introduced as a control technology to minimise in-service diesel emissions in an effort to reduce worker exposure to DPM, a known carcinogen.

This paper focuses on testing the filtration efficiency and in-situ effectiveness of DFEs as tested by current testing protocols in Australia through a statutory method — MDG 43 and through an in-service method — MDG 29.

Methodology

Two different approaches were undertaken to measure the filtration efficiency of DFEs currently being used in the Australian coal mining industry. These are described in more detail below.

First method — MDG 43 Statutory Method using an engine dynamometer

MDG 43: Technical standards for the design of diesel engine systems for use in underground coal mines (5) is the current Australian statutory method for DPM testing from the exhaust system of diesel engines. The method as described in section 3.7 of MDG 43 states:

> 1. The diesel engine system must be operated at an intermediate speed at full throttle setting for at least six hours with a clean particulate filter installed. The test must be carried out with the engine dynamometer set at a speed priority mode, with the torque values decreasing as filter blockage increases.
> 2. Gaseous emissions, exhaust backpressure and exhaust temperature must be recorded at the start and end of the test.
> 3. DPM or EC readings, using a device that complies with section 8 of MDG 29:2008 (6), must be taken at 0, 5, 10, 15 minutes and then every 15 minutes thereafter for six hours. In addition, DPM readings should be taken each hour using a partial or full flow dilution tunnel.
> 4. For constant speed engines, this test must be carried out at rated speed at full throttle setting.
> 5. The diesel engine system must still be in a safe condition of use at the end of the six hours.

The filtration efficiency is then calculated as the percentage of DPM removed by the DFE as an average over the six-hour sampling period.

This methodology differs from that used in the United States where DFEs are approved by the Mine Safety and Health Administration (MSHA) following part 7 testing procedures in 61 Federal Register 55525 as described by Bugarski et al. (7). In this test, paper and synthetic DFEs are compared to a “gold standard paper DFE” the derivation of which is not publicly available and the actual filtration efficiencies are not reported. Furthermore, the MSHA test procedure prepares each filter for testing by loading it for several hours with DPM as a “degreening” process. No such “degreening” period is allowed in MDG 43 with a new filter being used from the commencement of testing. No specific details of the “degreening” process could be found in the literature.

The MDG 43 test method (5) was used in an experimental study to test four different DFEs that had been proposed for use on-site at a local coal mine. The four DFEs (Table 1) had either already undergone or been submitted for *“acceptance approval”* by the NSW Department of Industry, Skills and Regional Development. This approval required achievement of a minimum average filtration efficiency of 85% with a maximum backpressure of less than 10 kPa after six hours’ usage.

It was decided to test the filters over the first hour of use to see if the filters achieved their rated efficiency from the commencement of use. Each one of the four DFEs provided for testing was placed in a diesel test rig consisting of a Detroit Diesel 706LTE engine fitted with a hydraulic system to induce the required desired load as per MDG 43. Samples were collected at the commencement of the test and then at 15-minute intervals, pre- and post- the DFE being tested, by a high-volume pump with a flowrate of 10 liters per minute and collected on 37-mm SKC Inc quartz filters (catalogue number 225-401).

Table 1: Disposable Filter Elements tested

Filter identification	Filter type
A	Microfresh DA 100
B	Cosway C100A
C	VLI (5-04108101)
D	FST 115-12.5

All samples were forwarded to Sunset Laboratory Inc in Portland, USA for analysis by NIOSH Method 5040 using the oxygen injection point as the elemental carbon (EC) separation cut point (8). All results were reported as mg/m^3 EC. Sample results were collated and analysed using IBM Statistical Package for the

Social Sciences (SPSS version 21). Analysis of variance was used to determine any difference in filtration efficiencies between the four DFEs.

Second method — MDG 29 Statutory Method using in-service raw exhaust

The in-service method based on MDG 29: Guideline for the management of diesel engine pollutants in underground environments is the statutory raw exhaust testing method for DPM in underground mine vehicles (6). This test involves the vehicle being suitably restrained to restrict movement, the transmission placed in third gear and then a 20-second period of idle followed by a 20-second period of full load with a subsequent 20-second period of decay to idle resulting in a 60-second overall sample collection. The pre-sampling point was collected at the statutory gas sampling point on the engine manifold prior to any after-treatment devices, and the post-sample collected after the last after-treatment device. The filtration efficiency was calculated from the pre- and post-DPM values as an average percentage over the 60-second test period.

Due to operational conditions at the mine, only filter A (Microfresh DA100) and filter C (VLI 5-04108101) could be tested using the in-service method. Filter A was tested in LHD vehicles (Caterpillar C7 engine), while filter C was tested in a personnel transportation vehicle (Perkins 1006-6 engine). Testing was undertaken using a Diesel ChekMate® Mark II (ERP Engineering Pty Ltd) raw exhaust diesel particulate instrument calibrated in mg/m^3 EC. The Diesel ChekMate® is a screening device that measures the increase in backpressure as DPM is collected on a quartz filter. This is then calibrated against EC measured by NIOSH Method 5040.

Results

The results of both testing methods are presented as follows.

MDG 43 Statutory Method Results

The results of testing of pre- and post-DFE EC analysis during the first 45 minutes of testing as per MDG 43 are shown in Table 2. A comparison of the pre- and post-DFE collection filters are shown in Figure 4, while Figure 5 shows the comparison of filtration efficiencies of the four DFEs tested.

Table 2: Elemental carbon analysis at baseline and 15-minute intervals

Filter identification	Time (min)	Pre-DFE EC (mg/m^3)	Post-DFE EC (mg/m^3)	Filtration efficiency (%)	*P*-value
A	0	27.5	0.07	99.7	0.0001
	15	25.3	<0.01	100	
	30	26.6	<0.01	100	
	45	26.2	<0.01	100	
B	0	22.4	0.2	99.1	
	15	24.2	0.03	99.9	
	30	20.5	0.06	99.7	
	45	21	0.03	99.9	
C	0	32.2	6.2	80.7	
	15	31.4	2.2	93	
	30	29	0.1	99.7	
	45	28.8	0.04	99.7	
D	0	27.2	20.6	24.3	
	15	27.6	15.4	44.2	
	30	27.6	10.3	62.7	
	45	28.5	8.2	71.2	

Figure 4: Images of collection filters pre- (left) and post- (right) individual DFEs prior to NIOSH Method 5040 analysis.

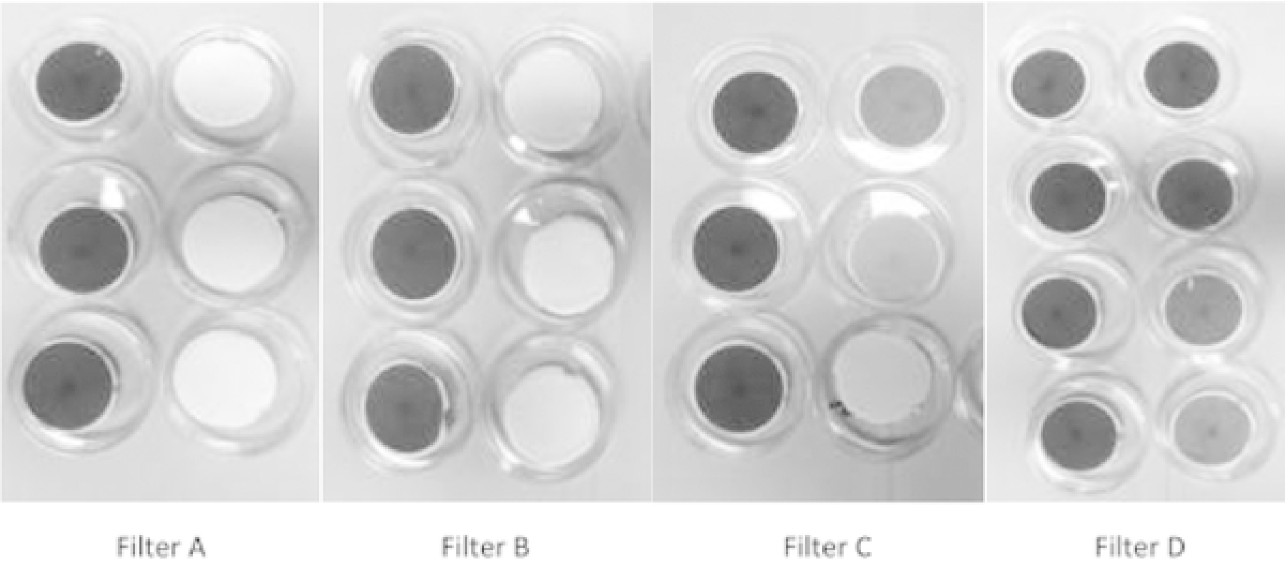
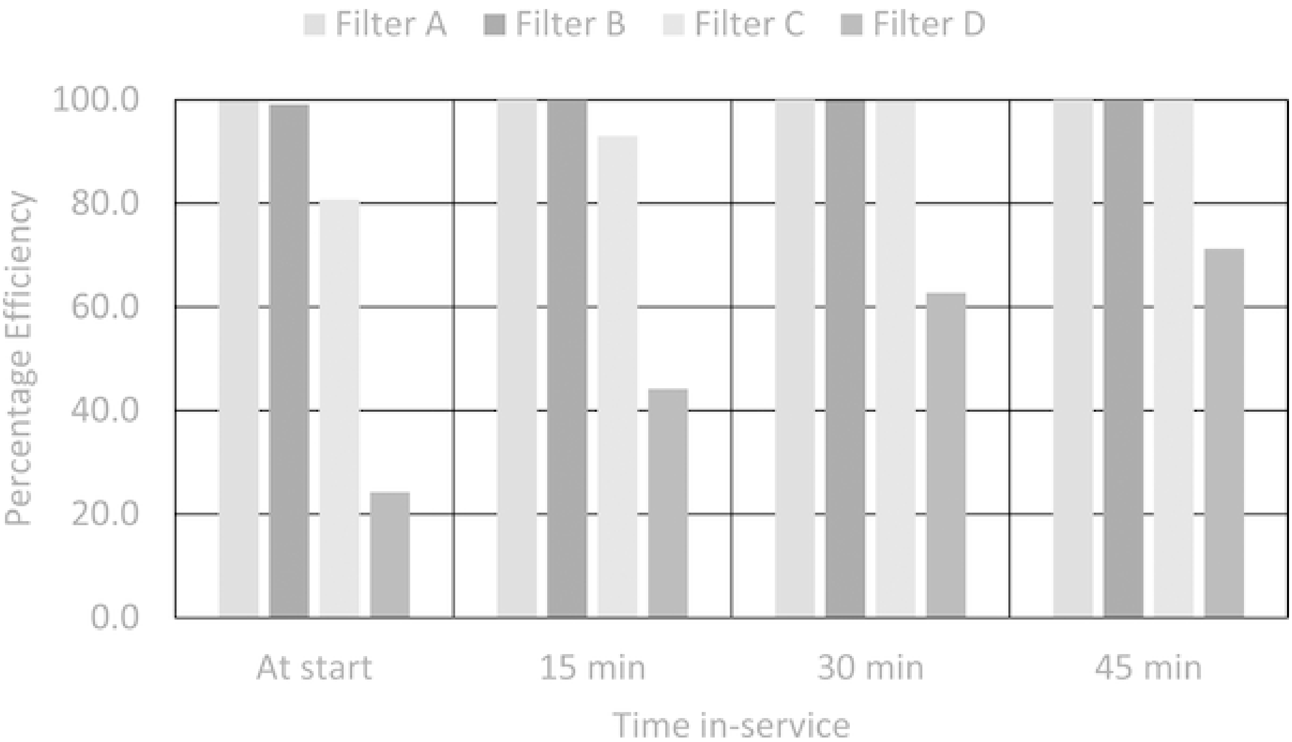
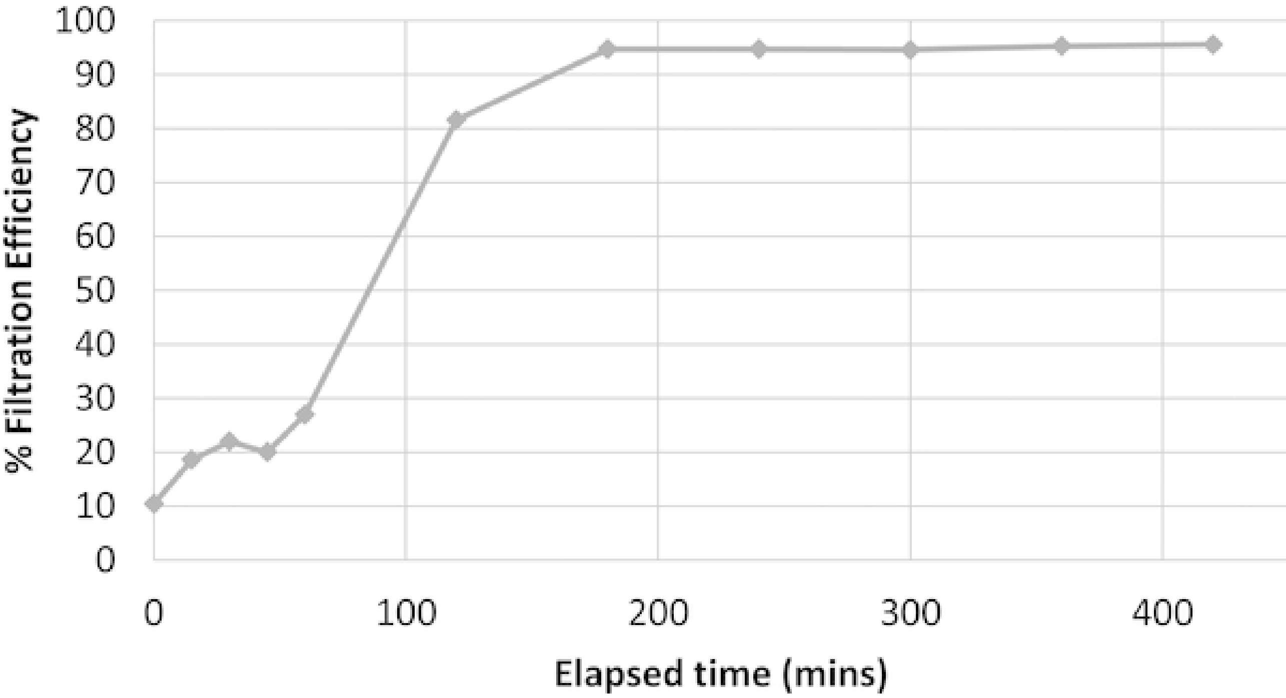


Figure 5: Individual DFE filtration efficiencies over time.



This data are consistent with that produced in a report where a longer duration test of approximately seven hours on filter D was done using the same test rig and load as the short test. In this instance, a calibrated Diesel ChekMate® Mark II diesel particulate analyser not NIOSH Method 5040 was used to measure the pre- and post-EC. The results of this testing are provided in Figure 6.

Figure 6: Filtration efficiency of Filter D during prolonged testing.



MDG 29 Statutory Method Results

The tests using the in-service method produced contrasting results to that expected as all filters tested were reported by their manufacturer to have a filtration efficiency of >85% based on the MDG 43 statutory test method. The average filtration efficiency of two types of DFEs across a mine diesel fleet using in-service testing is provided in Table 3. The DFEs were tested when first fitted to a vehicle and then again just prior to replacement. Issues such as leaking canister seals, loose or missing canister lid retaining mechanisms were identified and where this had occurred, data were removed from the results in Table 3. All filters were as recommended by the vehicle manufacturer or equivalent.

Table 3: Diesel feet average filtration efficiency of two types of DFEs using the in-service testing method

Vehicle type	Filter type	Filtration efficiency New filters (%)	Filtration efficiency Used filters (%)
Personnel Transportation Vehicle	VLI (5-04108101)	62	53
Load Haul Dump	Microfresh DA 100	69	50

During the in-service testing study period, a personnel transportation vehicle that underwent a major overhaul (designated as Code D) and returned to the site was tested as part of the study. Since its return to the site, the vehicle had only been operational for two hours with new filters fitted, thus the “*degreening*” process as practiced by MSHA in the United States would be complete. The results provided in Table 4 show that even after a two-hour “*degreening*” period, the in-service filtration efficiency was only 29%.

Table 4: In-service personnel transportation vehicle testing post-major engine overhaul

Filter type	Test location	EC results (mg/m^3)	Filtration efficiency (%)
VLI (5-04108101)	Pre-DFE test	14	29
	Post-DFE test	10	

To verify the above results, the quartz filters from the Diesel ChekMate® DPM instrument were analysed by NIOSH Method 5040, which confirmed the Diesel ChekMate® results. A thorough inspection of the exhaust system and DFE canister found no leaks and exhaust backpressures were low (<5 kPa).

Discussion

Testing of the four DFEs has identified several anomalies in the time filters take to achieve their maximum filtration efficiency. Filter C showed that it took up to 30 minutes to achieve its maximum filtration efficiency, filter D had not achieved its maximum filtration efficiency by 45 minutes, while filters A and B achieved their maximum filtration immediately ($P = 0.0001$). To verify if these anomalies had always existed, a review of the original Tower Colliery study was undertaken (4). It showed that although the filter media had changed in the DA 100 type filters between 2004 and 2018, such that direct comparisons could not be made, the data highlighted that even though the test-rig/dynamometer data indicated a filtration efficiency of 85%, in-service testing at the time showed lower filtration efficiencies (Table 5).

Table 5: Tower Colliery DFE filtration efficiency

Filter type	Operating hours	Filtration efficiency (%)
	New	*85.9*
Microfresh DA 100	16	71.5
	44	77.5

In-service testing would be able to identify issues such as leaking canister seals and loose or missing canister lid retaining mechanisms which would compromise DFEs and allow more DPM to be emitted into the atmosphere. The results in Table 3 suggest that the DPM was either by-passing the filter in some manner or migrating through the filter media. It was noted that some of the LHD vehicles were operating at high exhaust system backpressures of up to 25 kPa which may result in poor sealing between the DFE and the canister housing thus allowing exhaust to bypass the DFE.

A personnel transportation vehicle that underwent a major overhaul (designated as Code D) and had just returned to the site was examined by experienced mine mechanical engineers and found to have no obvious leaks in the filter canisters or evidence of the exhaust bypassing the filter canister thus suggesting the filtration efficiency should be in the vicinity of the manufacturers stated value of >85%. The vehicle was determined to be in perfect operational condition and had new filters fitted that had been used for two hours yet when tested the filtration efficiency was only 29% (Table 4). Given that all avenues for the exhaust to circumvent the filtration system had been checked for leaks or bypassing, it can be surmised that migration of the diesel particulate through the installed exhaust filters could be potentially occurring. Discussions with a filtration specialist (9) presented the theory that given the low concentration of DPM in the exhaust (14 mg/m^3 EC) it may take some considerable time for the DPM to deposit on the filter (forming a cake) which is known to assist filtration and thus increase filtration efficiency. The scope of the current research did cover this possibility, but further research may establish if this theory has validity.

Irrespective of the cause, any time lag to achieve maximum filtration will result in increased levels of DPM being emitted from the exhaust into the mine atmosphere. This situation would increase worker exposure to DPM during this "*lag period*", a situation that is inappropriate and counterintuitive given that DPM is a known carcinogen and other filtration media are available that can achieve their maximum filtration efficiency from the commencement of exhaust passing through the DFE. This observation is supported by the longer test time on filter D (Figure 6) where maximum filtration was not achieved for 180 minutes or approximately 38% of an eight-hour work shift.

Under the testing protocol used by MSHA, all filters undergo a "*degreening*" process of several hours (7) before testing and thus the filtration efficiency if reported by MSHA would be artificially high for a filter placed in-service and expected to work immediately. This conclusion assumes that mine operators would "*degreen*" filters prior to use which would be a potentially hazardous process and an added cost. Research has been demonstrated that airborne concentrations of DPM downstream of a diesel engine fitted with a DFE, which was under constant load, were reduced by approximately 45% to 73% over an 11-hour sampling period (10). This research further highlights that it might take several hours before some currently used DFEs reach their terminal efficiency. This, in effect, means that workers are potentially being exposed to higher levels of a carcinogen than would occur with a DFE that reached maximum efficiency from the moment it was inserted into the filter canister. This is of critical concern for mines using filters with a significant "lag time" as no "*degreening*" of filters prior to use is known to occur in Australia.

Disposable Filter Elements used in the United States are classified as "*deep-bed*" filters and thus such filters become more efficient as the filter loading increases and the pathways through the filter become smaller and more restrictive (7). In addition, the filtration efficiency is also a function of engine DPM emissions, with higher engine emissions tending to produce higher efficiency numbers. Given that the challenge concentration from the engine in the transport vehicle reported in Table 4 is relatively low (14 mg/m^3 EC), it may take extra time for the DPM to build up on the inside of the filter media in order to improve filtration. If this process occurs with all in-service filters operating at mine sites, then the real filtration efficiency that occurs is potentially much lower than that indicated by the current MDG 43 testing method in Australia.

This conclusion is supported by research conducted in the United States where a filter similar to filter C was tested and the percentage reduction of elemental carbon achieved under "*high idle*" conditions (ie limited load on the engine), versus that when the engine was under maximum load (torque converter stall) was approximately 72% and 90%, respectively (11). The lower filtration efficiency at reduced engine load against the higher filtration efficiency at high engine load and the current research suggests that engine load and the resultant variation in emissions play an important role in the determination of the filtration efficiency of a DFE at any point in time.

Comparison of the current test data to that of 2004 data suggests that the discrepancy of in-service versus MDG 43 testing using a test rig/dynamometer may have existed for many years and that the filtration efficiency stated by the supplier using the test method in MDG 43 may not be that achieved when DFEs are used in operating vehicles. The results of testing reported in Tables 3 and 5 support this view.

Conclusion

Given the carcinogenic status of DPM, the practice of "*degreening*" DFEs before statutory testing has no sound basis when considering the potential health outcome being sought by using DFEs. Exposure to DPM should always be controlled, not just when a filter has completed a "*degreening*" process. Notwithstanding the issues highlighted by this research, DFEs are still one of the most effective after-treatment technologies for DPM in coal mines; however, there is a need to ensure that exhaust filtration systems are well maintained and filter elements that are used commence filtering DPM immediately after they are inserted into the exhaust system. Such DFEs currently exist and approval acceptance criteria for future DFEs should include an assessment of the time the filter takes to commence filtration at its maximum filtration efficiency.

Moreover, the current testing protocol as required by MDG 43 should be reviewed and a routine "in-service" testing strategy of filtration efficiency at mine sites implemented. Such an approach would not only check the filtration efficiency of the filter but also highlight leaks in the exhaust filtration system and bypassing of the DFE canister. Such a strategy, if implemented, would provide mine personnel with greater confidence that the DFE system is lowering worker exposure to DPM.

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