Implementation of diesel particulate filter technology in underground metal and nonmetal mines

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ABSTRACT: Achieving substantial reductions in the exposure of underground miners to diesel particulate matter in a number of metal and nonmetal mines in the U.S. depends on the ability of the industry to widely implement advanced diesel emissions control technologies, primarily diesel particulate filter (DPF) systems. Recent field studies showed that diesel particulate filter systems with Cordierite and silicon carbide ceramic filter elements are capable of reducing concentrations of diesel particulate matter and elemental carbon by more than 70 and 90 percent, respectively. But those studies and several other attempts to implement DPF systems in underground mines revealed a number of relatively unique technical and operational challenges that are limiting industry-wide implementation of this technology. This paper provides detailed analysis of some of those challenges and short overviews of several projects launched by NIOSH Pittsburgh Research Laboratory in an attempt to provide the underground mining industry with more adequate DPF systems. These systems employ advanced technologies to overcome the most pronounced challenge, the regeneration of DPF elements installed on mining engines that generate relatively low exhaust temperature. This paper presents essential findings obtained through a long-term evaluation of DPF system with diesel fuel burner technology installed on a heavy-duty load-haul dump vehicle in an underground metal mine. In addition, the essential results of the laboratory evaluation of a popular on-highway DPF system which was adapted and optimized for underground mining applications will be summarized in this paper.

1 INTRODUCTION

Exposures of underground (UG) metal/nonmetal miners to diesel particulate matter (DPM) are significantly higher than those of any other occupation (Schnakenberg and Bugarski 2002). Compliance sampling conducted by the Mine Safety and Health Administration (MSHA) in 178 mines between 2002 and 2005 (Cash and Baughman 2005) showed that UG miners in precious metal mines are exposed to DPM concentrations as high as 3300 $\mu g/m^3$. The magnitude of those exposures was found to be directly related to the extent of use of diesel-powered equipment and the ability of mines to provide fresh air in the work zones. Ever since MSHA promulgated rule 30 CFR 57.5060 limiting exposures of UG metal and nonmetal miners to DPM, the mining community has been working on identifying technically and economically feasible strategies and technologies to reduce exposures to particulate matter and noxious gases emitted by diesel powered equipment. The challenge is designing, optimizing, and implementing technical and economical strategies and technologies that can accommodate requirements unique to UG mining environments and operations. In the majority of cases, solving these issues will require a multifaceted approach, a coordinated effort from several mine departments, and integral solutions.

The strategies available to the UG mining industry to reduce the exposure of miners to DPM can be generally divided into two groups: (1) strategies that are designed toward controlling the DPM once it has been released in the atmosphere; and (2) strategies that rely on controlling DPM emissions before they are released from the tailpipe.

The leading strategies for improvements in controlling diesel emissions released in the atmosphere are improvements in ventilation and more extensive use of environmental cabs and personal protective equipment (PPE). Ventilation is traditionally used to control concentrations of various pollutants in UG mines. The results of aforementioned MSHA compliance sampling indicate a need for improvements in ventilation in a number of U.S. metal and nonmetal UG mines. The first step toward making a safer work environment for UG miners with respect to diesel emissions is to provide sufficient quantities of fresh air to dilute the emitted carbon monoxide (CO), carbon dioxide (CO_2) and nitric oxide (NO), to bellow their respective 1973 American Conference of Governmental Industrial Hygienists (ACGIH) time-weighted average (TWA) threshold limit values (TLV) and the nitrogen dioxide (NO_2) below its 1973 ACGIH TWA TLV and short term exposure limit (STEL) values. The 1973 ACGIH TWA TLVs and STELs are currently used by MSHA to regulate the exposure of underground metal and nonmetal miners (30 CFR 57.5001 1995). Diluting DPM emissions sufficiently to reduce ambient concentrations below interim and eventually final U.S. standards (30 CFR 57.5060) requires that substantial additional quantities of fresh air are supplied to the work zones in underground mines (Schnakenberg 2001). Unfortunately, increased ventilation capacity is linked to a substantial increase in capital and operational costs (McPherson 1993). Some local improvements can be achieved with more effective management and distribution of available air quantities.

Environmental cabs are successfully used in UG and surface mining operations to control operator's exposures to dust, noise and some other pollutants. Nevertheless, MSHA surveys conducted in metal and nonmetal UG mines (30 CFR 57.5060) showed that adequately designed and maintained air conditioned and filtered environmental cabs might reduce personal exposures of underground miners to DPM by as high as 80%. Unfortunately environmental cabs do not provide protection to the workers outside of those enclosures. Costs associated with retrofitting existing vehicles and ordering new vehicles with environmental cabs are relatively high.

According to the current regulations (30 CFR 57.5060) the third available option to control DPM exposures, PPE should be only used to supplement engineering and administrative controls when those are found unfeasible or insufficient to reduce exposures to DPM.

A number of in-mine studies (McGinn 2004, Bugarski et al. 2005, Stachulak et al. 2005, Bugarski et al. 2006a,b) showed that a viable alternative to controlling concentrations of diesel pollutants released in UG environments is to reduce DPM and gaseous emissions from their diesel-powered fleet. In general, the concentrations of pollutants emitted by current UG mining diesel fleets can be significantly reduced by reducing engine-out emissions and implementing various exhaust aftertreatment technologies. In a number of instances an integrated approach is needed to achieve desired emissions reductions.

The adopted strategy should preferentially address vehicles that are highest contributors to the miner's exposure to DPM and gases. Typically, the largest contributors are heavy-duty production vehicles such as load-haul-dump (LHD) vehicles and haulage trucks that are often operated in relatively poorly ventilated areas. The contribution of increasingly popular light-duty vehicles, often powered by relatively high polluting engines, to the total DPM and gaseous concentrations in mine air should not be neglected (Rubeli et al. 2003).

Instituting a comprehensive emissions-based maintenance program for heavy-duty and light-duty diesel-powered vehicles should be the first step toward reducing concentrations of particulates and gases emitted by a diesel fleet (McGinn 2004). Establishing the in-use emissions from an existing diesel fleet is essential to the selection of an adequate emissions control strategy, the optimization of selected control technologies, and is a prerequisite for implementation of advance diesel emissions control technologies. Periodic emissions measurements should be also used to evaluate the effectiveness of the implemented control strategies and technologies.

Reductions in engine-out emissions can be also achieved by the use of reformulated fuels. The effects of water-fuel emulsions, blended biodiesel fuels, ultra low sulfur diesel fuel, and #1 diesel on concentrations of particulate matter and gases in mine air were evaluated by Bugarski et al. (2006b) during isolated zone testing at Stillwater Mining Company Nye Mine. This study showed that using the Lubrizol PuriNOx cold-weather and warm-weather water-fuel emulsions reduced EC concentrations by approximately 70% and 85%, respectively. The tested 20% and 50% soy biodiesel blends showed EC reductions of 49% and 66% respectively. The reductions were slightly less pronounced for the 20% and 50% yellow grease blends, 33% and 56% respectively. Several attempts to implement alternative fuels in underground nonmetal mines revealed problems related to compatibility of certain fuels and engine components.

Although substantial reductions in exposures of underground miners to DPM in a number of metal and nonmetal mines in U.S. can be achieved implementing the aforementioned strategies and technologies, the best results can be achieved by complementing those strategies with a widespread implementation of advanced aftertreatment diesel emissions control technologies. Such control technologies include diesel particulate filter (DPF) systems and filtration systems with high-temperature disposable filter elements (DFE). Recent field studies (Bugarski et al. 2006a,b) showed that diesel particulate filter systems with Cordierite and silicon carbide wall flow monolith filter elements are capable of reducing concentrations of DPM and EC in mine air by more than 70% and 90%, respectively. The same study showed that the disposable filter elements (DFE) from Donaldson and Filter Services reduced the vehicle EC contribution by 92% and 70%, respectively. The same DFEs reduced downstream TPM concentrations determined using gravimetric analysis by 84 and 58%, respectively. Despite their very high effectiveness in removal of EC and TPM, DPF systems have not been widely accepted by the UG mining industry. Various implementation issues were found to limit industry-wide implementation of this technology.

2 DPF IMPLEMENTATION ISSUES

The high demand for aftertreatment systems for the efficient control of particulate emissions from on-highway and off-road diesel-powered vehicles resulted in a rapid development of DPF technology. Two comprehensive long-term studies sponsored by the Diesel Emissions Evaluation Program (DEEP), one conducted at Noranda's Brunswick Mining and Smelting Mine (McGinn 2004) and one at the International Nickel Company's Stobie Mine (Stachulak 2005) demonstrated the potential of modern DPF systems for controlling DPM emissions in underground mines. Those studies also offered insight into the problems associated with the use of those systems on underground mining vehicles. Short-term studies conducted in SMC Nye mine (Bugarski et al. 2006a,b) also revealed a number of technical and operational challenges unique to UG mining applications.

The relatively large number of different types of diesel-powered vehicles currently operated in UG mines and the diversity of mining methods complicate the selection and implementation of this technology. Implementation is complicated by the fact that DPF systems are currently available to UG mining industries only as aftermarket retrofits for existing and newly introduced vehicles. Retrofitting aftermarket DPF systems on a wide range of UG mining vehicles requires a relatively large level of optimization and customization for individual applications.

One of the major technical difficulties associated with DPF systems is filter medium regeneration, which involves periodic oxidizing or burning of the accumulated DPM on the filter. In general, the filter can be regenerated using heat and temperature generated by the engine or by using heat and temperature provided by various external sources of energy. Systems which are using the former concept are known as passive systems. The latter concept is used in active systems. Due to their relatively lower complexity and operational and logistics requirements, passive DPF systems are the more desirable for underground operations.

Surveys of duty cycles for UG mining vehicles conducted across the mining industry revealed that temperature generated by engines that power a majority of light-duty and large a number of heavy-duty vehicles over regular duty cycles is insufficient to support passive regeneration of currently available uncatalyzed, and quite often catalyzed, filters. Data indicates that mining vehicles spend a significant percentage of time at engine operating conditions which do not favor passive regeneration. Data obtained at Noranda's Brunswick Mining and Smelting show that their vehicles spend an average of over 30% of time at low idle (McGinn 2004), engine operating mode that produce DPM emissions but does not support regeneration.

Several UG metal mines are currently operating heavy-duty vehicles such as LHDs and haul trucks with platinum coated passive DPF systems. Platinum-based catalyst formulations are found to be efficient in facilitating passive regeneration of filters by lowering the regeneration temperature from approximately 550°C (uncatalyzed DPF) to approximately 330°C (Jelles et al. 1999). Those formulations are also efficient in lowering CO and hydrocarbon emissions by oxidizing them to CO_2. Unfortunately they are also promoting conversion of NO to NO_2 (MSHA 2002). Isolated zone studies conducted by Bugarski et al. (2006a,b) showed a two or even three fold increase in emissions of NO_2 when certain types of platinum catalyzed DPF and DPF/DOC systems were used. Theoretically, vehicles with platinum coated DPF systems should be operated only in areas of UG mines where sufficient quantities of fresh air are supplied to dilute NO_2 concentrations to or below a ceiling limit of 5 ppm as established in MSHA standards at 30 CFR 57.5001.

The alternative solution is to use active DPF systems which are designed to collect DPM over a predetermined period of engine operation, e.g. one shift. Depending on design, regeneration is performed with the filter element remaining on-board of the vehicle or with it removed from the vehicle. The on-board regeneration process commonly uses an electrical heater but can use a diesel fuel burner. The regeneration of such systems can only occur with the vehicle parked with the engine off. Again depending on system design, regeneration can take anywhere from a half-hour or less (fuel burner) to eight hours. The off-board regeneration commonly uses electrical heaters or kilns designed for the purpose.

Stachulak et al. (2005) found that active systems with off-board and on-board electrically regenerated systems can be successfully used to control DPM emissions from light- and heavy-duty UG mining vehicles. The authors attributed difficulties with operating on-board regenerated system in underground mine to human error and stressed the importance of discipline and education. A majority of other mine operators found on- and off-board electrically regenerated systems to be too complex, delicate, and expensive to be widely implemented in underground operations.

Therefore, there is an apparent need for efficient DPF systems which will satisfy the following criteria: (1) regeneration spontaneously regenerates at relatively low exhaust temperatures; (2) does not produce secondary emissions of NO_2 and other pollutants;

(3) operates "transparently" to the operator; and (4) is robust and reliable.

3 OPTIMIZATION OF DPF SYSTEMS FOR UNDERGROUND MINING APPLICATIONS

NIOSH PRL has partnered with selected manufacturers of control technologies and the mining industry to develop and optimize several promising DPF concepts for UG mining applications and therefore facilitate the implementation of DPF technology in underground mines. This paper describes two of those projects which may provide mining industry with DPF systems that satisfy the aforementioned criteria.

3.1 *ArvinMeritor fuel burner DPF system*

The objective of the first project, conducted in cooperation with ArvinMeritor (AM), Commercial Vehicle Emissions, Troy, MI, was the field evaluation of a prototype DPF system that uses a diesel fuel burner to periodically increase the temperature of the full flow of diesel exhaust in order to initiate and support filter element regeneration.

Under NIOSH contract AM designed and fabricated the prototype fuel burner system for a heavy-duty production LHD from the underground mining fleet at the Stillwater Mining Company's (SMC's) Nye Mine located in Nye, MT. The vehicle was powered by a modern electronically-controlled turbocharged Deutz BF4M1013 FC MVS engine. The system shown in Figure 1 consisted of a vertically mounted uncatalyzed ceramic wallflow monolith filter element, the DuraTrap RC (Corning, NY), followed by a metal substrate diesel oxidation converter (DOC). The DOC was designed to control CO and hydrocarbon emissions during normal vehicle operation and the regeneration process. The original DOC had a platinum (Pt) based formulation wash-coated onto a substrate. After approximately 470 operating hours, the Pt DOC was replaced with a similar DOC with a palladium (Pd) based washcoat. The computer controlled diesel fuel burner is integrated on the inlet side of the DPF element.

The control box with fuel pump, air blower, and controller is mounted in the engine bay (see Figure 2). When activated, the burner ignites diesel fuel injected into the combustion chamber to heat the engine exhaust and filter element to about 650°C, a temperature sufficient to support DPF regeneration. The regeneration process was initiated at predetermined time intervals.

The system was installed on the LHD in January 2004. After the installation the vehicles was returned into production and DPF system was subjected to

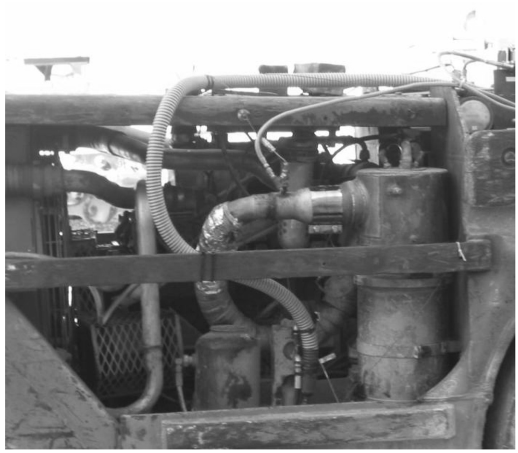

Figure 1. ArvinMeritor DPF system installation.

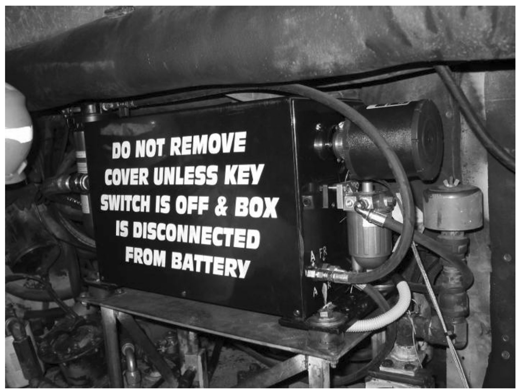

Figure 2. ArvinMeritor DPF system control box.

long-term evaluation. The objective of the study was to evaluate the suitability of the AM DPF system for controlling diesel particulate matter emissions generated during heavy-duty underground mining applications. The long-term field evaluation provided an opportunity to evaluate various aspects of implementation of this DPF system, such as installation and regeneration, in an underground mining application. During the evaluation the fuel burner, acting automatically at preset intervals, successfully regenerated the filter element.

After 470 hours in production the system was tested in the isolated zone at the Nye Mine. The objective of this testing was to establish the effects of two configurations of the AM DPF/DOC system on concentrations of aerosols and selected gases in mine air. Three tests were conducted, two with tested configurations (DPF with Pt- and Pd- DOCs) and a baseline in which the host LHD was equipped with a muffler. For each of the tests the vehicle was operated over the same simulated duty cycle and at a similar ventilation rate. The vehicle was fueled with #1 diesel supplied by a local refinery. This higher quality fuel was used by the mine in underground operations as a part of their strategy to reduce the exposure of miners to diesel emissions. The effects on tailpipe emissions were estimated from the results of aerosol and gas measurements performed at the upstream and downstream end of the isolated zone and at the vehicle. Several methods and instruments were used to determine concentrations of the aerosols in the incoming fresh air at the upstream station and in the contaminated air at the downstream and vehicle sampling stations. The gas monitors were used for real-time measurements and recording of concentrations of CO, CO_2, NO, and NO_2 at all three sampling locations. The details on the methodology and instrumentation used during this test are available in Bugarski et al. (2006b). The effects of each configuration were quantified by comparing the contaminant concentrations observed for the test when the vehicle was operated with the test configuration to those observed for the baseline test.

With the exception of some difficulties in the development phase the operation of this system was found to be relatively transparent to the vehicle operator. Despite the complexity this prototype system was found to be relatively reliable. The system required regular maintenance and couple of unscheduled repairs.

The isolated zone testing revealed undesired effects of the Pt catalyzed DOC on the tailpipe emissions of NO_2. The test on the AM DPF system with the Pt catalyzed DOC had to be terminated prematurely to prevent an overexposure of the vehicle operator to NO_2. During the initial stages of that test, the gas monitor at the vehicle sampling station recorded concentrations of NO_2 that were close to, or exceeded, the 1973 ACGIH TLV of 5 ppm. This limit is currently used by MSHA as a Ceiling Limit to regulate exposure of underground metal and nonmetal miners to NO_2 (30 CFR 57.5001). The Pt-catalyzed DOC was then replaced with one with a Pd-based catalyst. The AM DPF with the Pd DOC raised the average and peak downstream NO_2 concentrations approximately 30%, yet at the prevailing ventilation rate of 19 m^3/s (40,258 ft^3/min) used in the tests, the concentrations of NO_2 were well below 1973 ACGIH TLVs and the test was successfully completed. This test was extended for an additional three full cycles to assess the effects on emissions during the diesel fuel burner regeneration process.

The tests showed that the AM fuel-burner DPF system with a Pd catalyzed DOC reduced the EC concentrations by 92%. The same system reduced downstream concentrations of TPM by 69% (gravimetric measurements) and by 72% (TEOM 1400a measurements). The Pd-catalyzed DOC increased the sulfate concentration from 3.4 to 15.3 $\mu g/m^3$. Particle size distribution results indicated a 105% increase in the total particle number, possibly corroborating the hypothesis of increased sulfate aerosol concentrations. During the regeneration of the AM DPF system, the peak aerosol number concentration increased from about 1,666,000/cm^3, observed during the normal operation, to approximately 3,177,000/cm^3.

NO concentrations at the downstream and vehicle sampling locations were found to be generally lower during tests with the AM DPF having Pt and Pd DOCs. The slight reduction in NO is partially attributable to the conversion of NO to NO_2 by the DOCs.

The net contributions to the concentration of CO at the downstream and vehicle sampling stations of the LHD, equipped with the AM DPF with either a Pt or Pd DOC were found to be negligible. CO reductions can be attributed to the DOC's catalytic processes.

The system was successfully operated until March 2005. In fall 2004 ArvinMeritor decided to stop providing this system as a retrofit and to offer this system only as part of OEM solutions.

The DPF system with somewhat similar fuel burner concept is also offered by HUSS Umwelttechnik GMBH, Nürnberg, Germany. This system is using an on-board diesel fuel burner to regenerate a silicon carbide monolith element. In contrast to the AM system, the regeneration is performed while the engine is turned off. However, it requires less than 30 minutes to perform and can be done anywhere there is normally adequate ventilation (Rembor 2005). Thus regeneration can be performed at shift change or "lunch-time" periods. It appears to be suitable for retrofit applications for light- and heavy-duty UG mining vehicles and hence worthy of serious consideration.

3.2 *Low NO_2 Johnson Matthey Continuously Regenerating Trap system*

Johnson Matthey (JM) Royston, England developed a Continuously Regenerating Trap (CRT) system to control DPM emissions from on-highway trucks and urban buses (O'Sullivan et al. 2004). The core of the system is a Cordierite filter element. A platinum catalyst upstream of the filter is used to promote conversion of NO to NO_2. The exhaust gases, enriched with NO_2, pass to the filter element where they oxidize the collected particulate matter, thereby regenerating the filter. Since this reaction occurs at much lower temperatures than the reaction between particulate matter and oxygen, it is capable of passively regenerating when temperatures exceed approximately 250°C for at least 40% of the operation time. When the NO_2 reacts with the particulate matter, the products formed are carbon dioxide and NO. Inevitably, some NO_2 passes

Figure 3. Johnson Matthey CRT system.

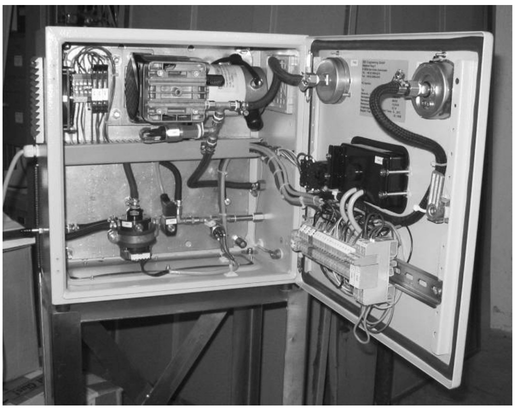

Figure 4. Johnson Matthey CRT system control box.

through the filter (Ayala et al. 2001, O'Sullivan et al. 2004). This process, commonly known as NO_2 slip, has prevented widespread application of the CRT system in underground mining, where the low exhaust temperatures needed for regeneration would be greatly appreciated.

JM engineers (O'Sullivan et al. 2004) proposed two potential solutions to the problem. The first solution uses an urea-based selective catalytic reduction (SRC) system to control both NO and NO_2 emissions. The second solution uses hydrocarbon (HC) injection onto a catalyst element after the filter which decomposes the NO_2. The former solution was deemed too complex and delicate for UG mining applications. The latter concept was adopted and pursued further.

NIOSH PRL sponsored construction of the prototype system shown in Figure 3. The NO_2 decomposition catalyst is shown on the right-hand side of the picture.

The operation of the system is controlled continuously using a HC injection controller that is designed to be mounted on-board of the vehicle (see Figure 4). The fuel is injected at the predetermined rates at exhaust temperatures above 250°C. The controller box contains the fuel pump, air compressor, and controller.

The test cell at University of Minnesota Center for Diesel Research Laboratory was used to optimize and evaluate this system. The system was tested using a 1999 Cummins ISM engine rated at 370 hp. An eddy-current dynamometer was used to test the engine using the ISO 8178 8-Mode Steady State Test and Inco Transient Cycle. The engine was fueled with the required ultra low sulfur fuel. This fuel, supplied by Consumers' Co-operative Refineries Ltd. Saskatoon, Saskatchewan, had average sulfur content less than 15 ppm by weight.

The particulate matter and gaseous emissions were established for three test configurations: (1) engine only, (2) engine equipped with JM CRT system, and (3) engine equipped with JM CRT system with HC injection and NO_2 decomposition catalyst. The emissions from the JM CRT system were used to optimize the rate of hydrocarbon injection. After the system was optimized the effects of hydrocarbon injection on NO_2 slip from the CRT system were evaluated.

The effects of the three configurations on the concentrations of NO, NO_2, CO, as well as non-methane hydrocarbons (HC), and the effects on the mass emissions of diesel PM (gravimetric) and elemental carbon (NIOSH 5040 analysis) were established using an array of instrumentation.

The tests with the JM CRT system (Zarling et al. 2005) showed that the system reduced on average DPM emissions by more then 90% and EC emissions by 95%. At the several test modes the system substantially increased fraction of NO_2 in total NO_x emitted by the test engines. When engaged the HC injection and NO_2 decomposition catalyst reduced NO_2 emissions out of the CRT system below those produced by the engine alone. The remaining issue is control of NO_2 slip at exhaust temperatures below 250°C.

After completion of laboratory development and evaluation, the JM CRT system with HC injection will be subjected to long-term field evaluation. The system will be installed on a heavy-duty underground mining vehicle and evaluated in production for at least 1500 hours.

4 CONCLUSION

Implementation of advanced DPF technology plays an important role in efforts to reduce the exposure of UG miners to DPM in a number of U.S. metal and nonmetal mines. Developing and optimizing DPF systems for specific UG mining applications are essential for successful implementation of this relatively novel technology in underground mines. Two concepts described in this paper showed that it is possible to design DPF systems that will be able to operate and regenerate at relatively low exhaust temperatures without introducing the risk of exposing miners to elevated NO_2 concentrations. Field evaluation of the prototype AM system showed that engineering of a rather complex DPF system with a fuel burner to a reliable and dependable system transparent to a vehicle operator requires concerted efforts of both the filter supplier and mine operator. If successfully completed, the JM CRT system with NO_2 slip control will provide the mining community with a much-needed viable solution for controlling DPM emissions without an adverse increase in NO_2 production. The findings from these two studies should facilitate the implementation of DPF technologies in underground mines and ultimately lead to reducing miners' exposure to DPM.

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