A Collaborative Research Project to Evaluate Diesel Emission Control Strategies.

Winthrop F. Watts, Jr., U.S. Bureau of Mines, Minneapolis, MN 55417-3099
Mark G. Ellis, American Mining Congress, Washington, D.C. 20036-1662
Robert A. Haney, Mine Safety and Health Administration, Pittsburgh, PA 15236-0070
Bruce K. Cantrell, U.S. Bureau of Mines, Minneapolis, MN 55417-3099
Kenneth L. Rubow, University of Minnesota, Minneapolis, MN 55455-0111
George P. Saseen, Mine Safety and Health Administration, Triadelphia, PA 26059
Todd R. Taubert, U.S. Bureau of Mines, Minneapolis, MN 55417-3099.

Abstract. The American Mining Congress (AMC) and the U.S. Bureau of Mines (BOM) have formed a collaborative research team to develop, implement and evaluate a comprehensive control strategy to reduce diesel particulate matter (DPM) concentrations without degrading other air quality parameters. The project is being conducted at two underground noncoal mines operated by the American Smelting and Refining Company (ASARCO). Other participating organizations include Caterpillar, Inc., the Mine Safety and Health Administration (MSHA) and the University of Minnesota (UMN). After extensive baseline information and air quality data are collected, available control strategies to reduce DPM exposures will be implemented individually or in combination and evaluated. This paper describes the objectives and protocol of the collaborative effort to evaluate diesel particulate control technology.

Introduction

A miner working underground where diesel engines are used is exposed to a wide variety of highly variable exhaust pollutants. These include noxious gases such as carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2), hundreds of different hydrocarbons (HC's), and DPM. The National Institute for Occupational Safety and Health (NIOSH) (*1*)[1] and the International Agency for Research on Cancer (*2*) (IARC) have respectively declared whole diesel exhaust to be "potentially" or "probably" carcinogenic.

The U.S. Mine Safety and Health Administration (MSHA) regulates some diesel exhaust pollutants such as CO, CO_2, NO, NO_2, and SO_2 and has proposed revised air quality standards for these and other contaminants (*3*). MSHA also certifies and approves diesel engines and has proposed new regulations in this area (*4*). In 1988, an MSHA Diesel Advisory Committee published their findings and recommendations (*5*) on standards and regulations for diesel-powered equipment in underground coal mines. Among the many recommendations was that the Secretary of Labor set in motion a mechanism whereby an appropriate DPM standard could be set and MSHA published an advance notice of proposed rulemaking for DPM in 1992 (*6*).

It is clear that mines using diesel equipment will be impacted by pending and future MSHA regulations and that DPM is the primary pollutant of interest. In 1993, AMC approached the BOM with several ideas for a joint diesel research project. AMC organized several meetings, which included representatives from industry, government and academia. Initially the discussion centered around the evaluation of aerosol instruments and analytical methods for measuring DPM concentrations underground. However, a consensus was reached to expand the scope of research with a goal to systematically evaluate control strategies to reduce diesel emissions, to

---

[1] Italicized numbers in parentheses refer to items in the list of references.

determine how much improvement in air quality is obtainable, at what cost. The primary objective is to develop, implement and evaluate a comprehensive control strategy to reduce diesel particulate matter (DPM) concentrations at an underground noncoal mine with a secondary objective to compare aerosol sampling and analytical methods for DPM. The shift in focus is attributed to the large amount of information already available on the different sampling and analytical methodologies for DPM, and the lack of information on in-mine evaluations of diesel emission control strategies. Potential control strategies include: improved diesel engine maintenance, optimized mine ventilation, modification of operator work practices, improvement of fuel quality, use of personnel protective devices, use of modern exhaust aftertreatment devices, use of modern engine technology, and combinations of these strategies. The objective of this paper is to describe the objectives and protocol of the collaborative effort to evaluate DPM control technology.

Project Organization

The BOM agreed to provide the technical leadership, coordination and direction for this project. The large scale and complexity of the project were immediately recognized, and the Bureau and AMC agreed to seek technical expertise from other organizations to ensure the project's success and the acceptance of the results. With this in mind, AMC formed an ad hoc technical advisory committee to assist the BOM in the planning and review process. AMC encouraged member companies to voluntarily participate. Caterpillar, Inc., Deutz, and Racal, agreed to provide technical expertise and equipment, and a number of other companies are contributing human resources to help carry out the field research. AMC also agreed to contribute $100,000 to offset some of the project's costs, especially costs incurred by the participating mines.

The Bureau and AMC also asked MSHA and the UMN to participate in the project. MSHA brings unique capabilities to the project. These include technical expertise in aerosol sampling, ventilation and diesel engine certification and approval, as well as additional hardware and human resources. The UMN is contributing technical expertise in aerosol monitoring with special emphasis on the in-use evaluation of personnel protective devices such as Racal airstream helmets. The UMN is receiving support from a grant from the Generic Mineral Technology Center for Respirable Dust and through a contract with the AMC.

Mine Selection

Three potential mines were screened to determine their suitability to host the collaborative study. These mines included a salt mine, a zinc mine and a trona mine. Criteria for participation included: (1) a highback room and pillar, dieselized, noncoal mine, (2) DPM concentrations around 1.0 mg/m^3 or higher, (3) measurable ventilation airflow, (4) and a commitment from the mine's management to fully support the objectives of the project. Each mine was visited at least once. During these visits the project was overviewed for mine management, the mine was toured, ventilation measurements were made and a limited number of aerosol samples were collected to determine DPM and respirable dust concentrations. Samples for NO and NO_2 were also collected at some or the mines, and MSHA provided detailed ventilation and DPM data derived from previous field surveys whenever possible. Based on the initial screening the salt mine was chosen as the host mine. Shortly thereafter a catastrophic geological event occurred, which caused the mine to be flooded with water, and the mine was forced to withdraw from the project.

Three additional mines were screened; another salt mine and two lead/zinc mines. Both lead/zinc mines were selected as test mines. The mines, West Fork and Sweetwater, are located near Viburnum, Missouri, and are operated by ASARCO. A formal agreement, outlining the proposed work and project guidelines, was signed by AMC, the BOM and ASARCO.

The major objectives are to develop, implement, and evaluate a comprehensive industrial hygiene plan for to reduce DPM concentrations, and to evaluate DPM aerosol sampling and analytical methods. This research is being conducted at the West Fork mine. The objective of the Sweetwater mine study is to evaluate the effect of a new ventilation shaft on DPM exposure before and after the shaft becomes operational. The investigators felt this was a unique research opportunity that fell within the scope of the overall project goals, and that would not require a large commitment of additional resources.

Mine Description

The ASARCO West Fork and Sweetwater mines are located on the southeastern edge of the Ozark Mountains near Viburnum, MO. The principal economic minerals are galena (lead sulfide) and sphalerite (zinc sulfide). The sphalerite also contains some silver. Both mines use the room and pillar method of mining and produce an estimated combined tonnage of 124,000 mt of lead, 20,000 mt of zinc and 9,950 kg of silver, all contained in concentrates.

At West Fork blasted rock and ore is mucked by 5.35 m^3 front-end loaders into 32 mt haul trucks for transport to a 181 mt capacity truck dump, a vertical chute cut out of rock. The fractured rock is gravity fed onto conveyor belt and carried to a crusher. The crushed rock is hoisted to the surface and deposited in an ore storage bin.

At Sweetwater broken ore and rock are mucked by 9 mt capacity load-haul-dump units which transport the material to centrally located raises, or by 7.2 mt front-end loaders into 32 mt haul trucks for transport to the raises if the haul distance is too long. Broken ore passes down the raises into 10 - 16 mt railcars pulled by a diesel locomotive. The railcars dump their loads into a crusher, and the crushed ore drops to a skip pocket where it is loaded on skips for hoisting to the surface and storage in a coarse ore bin.

Phase 1 Experimental Protocol

The project is divided into phases and only the phase 1 experimental protocol will be discussed in detail. Planning for the subsequent phases is very much dependant upon the information and data gather during phase 1. Most of the discussion will be devoted to those portions of the study being conducted at the West Fork mine. The West Fork mine protocol is divided into the following sections; diesel fleet description, diesel engine maintenance evaluation, ventilation survey, aerosol sampler and analytical method comparison, baseline air quality survey, and personal protective equipment evaluation. Each section is described briefly below. This is followed by a short description of the Sweetwater mine protocol.

Diesel Fleet Description

The diesel fleet accounts for a large portion of a mine's operating cost and efficient use is required to maximize production while minimizing costs. The objective of the diesel fleet description is to obtain and analyze information about the fleet, its operation, and operator work practices so practical recommendations can be made that may reduce pollutant levels in the mine without adversely impacting production or safety. These recommendations, individually, may not greatly impact pollutant levels, but in combination with other recommendations, could provide a measurable reduction. The description will include a detailed inventory of all diesel equipment and a time and motion study of the heavy-duty production vehicles to evaluate operator work practices.

The diesel inventory will include descriptive information about each piece of equipment, such as equipment type, scheduled availability, engine type, age, general location and use patterns. The time and motion study will record the mucking activities of the production vehicles in the test sections. The mucking cycle will be broken into the various elements that make-up the job. The time needed to complete each element will be recorded as will production tonnage. By studying each element, areas of improvement can be identified and changes made to maximize production and minimize exhaust emissions.

Two trucks and two front-end loaders will be equipped with a datalogger during their normal operation. The datalogger will map the engines speed, engine exhaust temperature, boost pressure, and engine fuel pump rack position during production mining cycles. This will provide information to define the duty cycles of the production vehicles.

Diesel Engine Maintenance Evaluation

Diesel exhaust pollutant concentrations underground are dependant upon the quantity of ventilation air and the exhaust emission rates. Inadequate maintenance, improper adjustments, wear, and other factors will cause changes in diesel exhaust emission rates. For example, it has been shown that on an engine with approximately 12.5 kPa (50 in H_2O) intake restriction and 20 percent overfueling, DPM emissions can increase by 1038 percent and CO by 445 percent (7). Proper maintenance including periodic repairs and adjustments, detailed maintenance schedules and accurate records, and proper procedures are an important part of a mine's overall strategy for reducing worker's exposure to diesel emissions. A good maintenance program can prolong or restore near-original performance of an engine and maximize vehicle productivity and engine life while keeping exhaust emissions at acceptable levels.

The objective of the diesel engine maintenance evaluation is to examine the West Fork mine's current maintenance practices, determine the state of engine maintenance of the production vehicles currently in-use, make recommendations to improve engine emissions, and implement cost-effective improvements. The current maintenance procedures used at the mine will be compared to those recommended by the engine manufacturer for the production vehicles. This will involve evaluation of the maintenance schedule, paper trail for record control, and review of the maintenance procedures. Diesel fuel and used engine oil will be analyzed to determine fuel quality and to determine metal content in the oil. Excess metal content in the lubrication oil is an indication of accelerated component wear. Production vehicle engines will be inspected to determine component settings and fuel system condition. An authorized representative of the engine manufacturer will check and repair if necessary the following:

1. Engine specifications including; injection timing, injector nozzle crack pressure, nozzle leak down and spray quality, valve lash, air fuel limiter setpoint, fuel pump calibration setting for horsepower (rack setting), high idle speed check, intake vacuum check, exhaust backpressure check, and oil pressure.
2. The injection nozzles, fuel pump, governor, cylinder head and turbocharger part numbers including will be recorded as well as any non-original equipment manufacturer parts.
3. The cooling system will be inspected for cracks in the radiator, plugging of the radiator, radiator core damage and thermostat operation.

Based on results from the engine inspection and results of the post inspection emission testing described below, the engine with the highest DPM emissions will be selected and torn down. Results of the teardown inspection will help determine the causes for the higher emissions. The teardown will document the condition of the following additional items, which will be replaced if necessary: piston, piston rings, liners, intake and exhaust valves, cylinder head, camshaft and aftercooler core.

Limited tailpipe emissions testing will be conducted on engines used in the production equipment. These data will establish baseline DPM emissions and identify engines with excessive emissions. These measurements will be taken under torque converter stall conditions before and after the inspections described above. A minimum of three repeats of each test will be taken for each production vehicle. DPM will be measured using a model BG-1 micro-dilution test stand.

Ventilation Survey

The primary means of reducing exposure to diesel exhaust pollutants is through dilution by the mine ventilation system. The concentration of pollutants is indirectly proportional to changes in ventilation airflow, that is, as the airflow increases the pollutant concentrations decrease. The rule-of-thumb for ventilation system airflow requirements where diesel engines are operated is between 3.8 and 7.6 m^3/kW (100 and 200 ft^3/bhp). Recent experience has shown that this airflow will maintain DPM levels at approximately 1.0 to 1.5 mg/m^3 (*8*).

The objective of the ventilation survey is to describe and evaluate the existing ventilation system for the mine and provide a model suitable for computer simulations to evaluate changes that could enhance the performance of the ventilation system. The system will be described in terms of airflow distribution and ventilating pressures. A description of the mine ventilation system will allow the investigators to:

1.) Evaluate and select fixed point monitoring sites for the air quality tests where airflow determinations can be made; 2.) determine if changes in the ventilation system such as reduced leakage or increased fan capacity can significantly improve the ventilation system; and 3.) determine the feasibility of redesigning the ventilation system to incorporate concepts such as parallel air splits or additional air shafts.

Four types of data will be collected throughout the mine.

1.) Airflow measurements will be taken using vane anemometers, smoke tubes and measuring tapes. Brattice lines will be examined to determine points of excessive air leakage.

2.) Ventilation pressure measurements will be made at points with know elevations using Magnehelic water gages.

3.) Fan measurements will be made to determine the operating point of main mine fans. These measurement will require the use of a Pitot-static tube and Magnehelic water gage; a vane anemometer; and volt and amp meters.

4.) The evaluation of ventilation in the production sections will consist of a review of fan and tubing position and if possible the determination of airflow patterns. Smoke tubes and possibly a tracer gas will be used to make this evaluation. The position and operation of auxiliary fans and tubing systems will also be checked and recommendations to optimize fans position will be made if required.

Upon completion of the ventilation survey data will be analyzed and recommendations will be made to optimize the mine's ventilation system.

Aerosol Sampler/Analytical Method Comparison

Questions still remain concerning the interpretation of the various diesel aerosol measurement techniques which are described in detail elsewhere (*9*). The in-mine comparison will permit proper interpretation of aerosol results. In addition, the mine atmospheres at the West Fork and Sweetwater mines are affected by fogging during the spring and summer months. The comparison tests will determined if fogging affects the performance and interpretation of aerosol data.

A test chamber containing thirty sample ports will be used to conduct these tests. The sample chamber inlet is equipped with two cyclones that match the American Conference of Governmental Industrial Hygienists respirable dust criteria, at airflows of 25 to 30 L/min. A DPM sampling device and a sampling pump will be connected to each of the sample ports. For these tests, sample pumps will be calibrated and operated at either 1.0 or 1.7 L/min. The sampling devices will include size selective impactors developed by MSHA and the Bureau, the respirable combustible dust (RCD) technique developed in Canada and the elemental carbon approach under development by the National

Institute for Occupational Safety and Health (NIOSH). These aerosol measurement techniques and analytical methods are described in detail elsewhere (9).

At a flow rate of 1.7 L/min, the size selective samplers would have a cut point of 0.9 µm. Groups of 10 samples were chosen so that a difference between samplers of 0.1 mg/m^3 would be statistically different at an a priori coefficient of variation of 5 pct. Seven to 10 sampling days will be required. This number is based on a t-test of the difference between two means requiring a 95 pct certainty.

Size selective and respirable combustible dust (RCD) samples will be analyzed gravimetrically, with pre- and post weighing to 0.001 mg. Elemental carbon samples will be analyzed using the method developed at Sunset Laboratories for NIOSH. A 1.0 L/min flow rate will be used for a portion of the elemental carbon measurements to permit a longer sampling time. A series of 7 tests will be conducted using the dust chamber. For each test, 10 of three different sampling devices will be attached to the chamber. The sampling chamber will be located at a fixed site monitoring locations in the production area. The sampling time will be varied to obtain various mass loadings on the samplers. For high loading the samplers will operate for most of the shift. For low mass loadings the samplers will operate for approximately 1 to 3 hrs depending on the ambient dust concentration. Prior to the test, sampling pumps will be calibrated to the desired flow rate using the resistance of appropriate sampling device.

Baseline Air Quality Survey

The baseline air quality survey will establish CO, CO_2, NO, NO_2 and DPM aerosol concentrations before control strategies are implemented. Similar measurements will be collected after each control or combination of controls is put into place.. The difference between the two sets of measurements is a measure of the effectiveness of the control strategy. Data will be normalized to account for differences in ventilation, production and fuel usage. The baseline air quality survey has the following objectives.

1.) Measure the flux of aerosol generated on the working sections,
2.) Measure the exposure of the LHD operator to diesel aerosol, and
3.) Measure the concentration of CO, CO_2, NO and NO_2 in the production areas to characterize air quality.

Aerosol generated on the working section will be determined by measurement of the flux (F) of aerosol removed from the section by the ventilation. This is determined from the measured intake corrected DPM aerosol concentration (C) measured in the air exhausted from the section and the quantity of exhaust air (Q) by:

$$F=CQ$$

This assumes that C is constant for all air exiting the section and Q can be accurately determined. The accuracy with which C and Q can be measured determines the resolution with which changes in F can be determined and consequently the efficiency of a control.

If C is not constant, then aerosol stratification exists in the exhaust air, F must be determined by:

$$F=\sum_i C_i Q_i$$

Here, C_i and Q_i are the intake corrected DPM aerosol concentration and air quantity for a portion of the exhaust from the section. The distribution of both of these quantities must be determined during the air quality measurements. The existence or absence of aerosol stratification will be determined prior to the baseline study so that appropriate modifications can be made to the final sampling protocol.

Exposure assessments of the vehicular operators will involve measurement of DPM aerosol near the breathing zone of the LHD operator. This will be done using size selective and RCD measurement techniques and will not involve stratification considerations.

The baseline air quality survey will be conducted during a period when the mine is performing normal mining operations. Sampling for DPM, CO, CO_2, NO and NO_2 will be conducted simultaneously at multiple locations. These locations include fixed sites upwind and downwind of the production equipment and on the production equipment. The fixed site samples will be used to measure the amount of aerosol produced in the operating sections as aerosol flux and the equipment monitors will assess exposure. If aerosol stratification exists, then an additional array of samplers at the downwind locations will be required to map the stratification. Aerosol samples will be collected using size selective, RCD and elemental carbon methods. Details on these methods are found elsewhere (*9*).

Personal Protective Equipment (PPE) Evaluation

The purpose of the PPE evaluation is to determine the protection factor associated with the use of the Racal Dust and Mist air purifying helmet system, Model AH21, under in-use conditions at the mine. Specifically, airstream helmets, worn by load-haul-dump (LHD) operators will be evaluated to determine their application for protecting workers from exposure to DPM. Particle concentrations inside and outside of helmet will be measured to determine the level of respiratory protection afforded to the worker. Particle sampling probes and size-classifying samplers will be used to determine the particle concentration in specific size ranges.

The instrumentation package will consist of a sampler to size-classify and collect respirable-size particles. Each sampler will consist of three stages; a 10 µm cutpoint impactor, a 0.8 virtual impactor and an afterfilter. The sampling inlet will be a modification of an inlet previously developed at the UMN for use in a NIOSH funded "powered air-purifying respirator" project (*10*). The sampled particles will be collected in two size ranges for subsequent gravimetric analysis. These size ranges are from 0 to 0.8 µm and 0.8 to 10 µm. Two identical samplers will be used with each respirator. One will sample particles inside the respirator near the breathing zone, and another, located immediately outside the respirator, will measure the mine air particle concentration. The air sampling flow rate will be 4 to 5 L/min, rather than the more commonly used 2 L/min, in order to increase the quantity of particles sampled inside the respirator and decrease uncertainty in the gravimetric analysis. The uncertainty in the gravimetric analysis is 0.015 mg. One personal sampler pump will be required for each sampler.

To determine the variability among respirators and workers, six identical air stream helmets will be evaluated simultaneously. Helmets will be worn by the 4 production vehicular operators and by 2 research personnel stationed at stationary sampling which is anticipated to have the highest aerosol concentrations. This will require 12 particle samplers and 12 personal sampler pumps. A total of ten tests will be conducted with each respirator. The field sampling will be conducted during one shift/day over a 10-day period. Project personnel will coordinate the use of the respirators with the mine employees, perform fit testing prior to study and monitor the equipment during the work shift to ensure correct operation.

Sweetwater Mine Protocol

In August, 1994 the Sweetwater mine finished sinking a new ventilation shaft. This shaft serves the south part of the mine and increased ventilation air quantities by about 5,660 m^3/min (200,000 ft^3/min). Prior to the completion of the shaft, two days of sampling were conducted at the mine to determine DPM concentrations. Forty-two RCD samples were collected at six locations. These included three stationary sites (upwind of the production vehicles in the intake airway, downwind of the production vehicles and in the return airway) and three mobile locations (two trucks and on a front-end loader). In addition to the aerosol measurements information was collected on production tonnage, ventilation airflow, mucking cycle and vehicular use. Results from this survey will be compared to a similar survey to be conducted shortly after the ventilation shaft is completely operational to determine the reduction in DPM concentrations and the exposure of production vehicular operators to DPM. This will conclude the research to be conducted at the Sweetwater mine.

Subsequent Phases

Data gathered during the phase 1 study at the West Fork mine will be analyzed and a detailed plan to reduce DPM exposure will be prepare during phase 2. Potential control strategies include: improved diesel engine maintenance, optimized mine ventilation, modification of operator work practices, improvement of fuel quality, use of personnel protective devices, use of modern exhaust aftertreatment devices, use of modern engine technology, and combinations of these strategies. The plan will be implemented in subsequent phases. One or two more air quality surveys will be conducted to determine the efficiency of the control strategies. Data will be normalized to account for differences in production, ventilation and fuel usage. In general, the strategies will be implemented in order of simplest or least costly to most complex and most costly. Data will be collected on the cost of implementation of the control strategies to determine cost efficiency. The project is expected to last approximately two years.

Summary

It is clear that mines using diesel equipment will be impacted by pending and future MSHA diesel regulations and that DPM is the primary pollutant of interest. AMC approached the BOM with several ideas for a joint diesel research project and AMC and the BOM have formed a collaborative research team to develop, implement and evaluate a comprehensive control strategy to reduce diesel particulate matter (DPM) concentrations without degrading other air quality parameters. The project is being conducted at two underground noncoal mines operated by the American Smelting and Refining Company (ASARCO) and involves participants from MSHA, Caterpillar, Inc, Racal, UMN and other AMC member companies. After extensive baseline information and air quality data are collected, available control strategies to reduce DPM exposures will be implemented individually or in combination and evaluated. This paper has discussed the objectives and protocol of the phase 1 portion of the collaborative effort to evaluate diesel particulate control technology.

The phase 1 protocol to be implemented at the West Fork mine is divided into the following sections; diesel fleet description, diesel engine maintenance evaluation, ventilation survey, aerosol sampler and analytical method comparison, baseline air quality survey, and personal protective equipment evaluation. A separate and smaller study of the impact of a new ventilation shaft on DPM at the Sweetwater mines was discussed. Upon completion of phase 1 all data will be analyzed and a plan to control DPM exposure will be prepared and implemented. Additional, in-mine air quality surveys will determine the efficiency and cost effectiveness of this control strategy. It is hoped that this type of collaborative research project will become a model for future joint research ventures involving government, industry and academic participants.

References

1. National Institute for Occupational Safety and Health. Carcinogenic Effects of Exposure to Diesel Exhaust. Current Intelligence Bull. 50, Dep. Health and Hum. Serv. (NIOSH) Publ. 88-116, 1988, 30 pp.
2. International Agency for Research on Cancer (Lyon, France). IARC Monographs on the Evaluation of Carcinogenic Risks to Humans; Diesel and Gasoline Engine Exhausts and Some Nitroarenes. V. 46, 1989, 458 pp.
3. Federal Register. U.S. Mine Safety and Health Administration (Dep. Labor). 30 CFR Part 56, et al. Air Quality, Chemical Sub-stances, and Respiratory Protection Standards; Proposed Rule. V. 54, No. 166, Aug. 29, 1989, p. 35769.
4. Federal Register. U.S. Mine Safety and Health Administration (Dep. Labor). 30 CFR Parts 7, 70, and 75 Approval Requirements for Diesel-Powered Machines and Approval, Exposure Monitoring, and Safety Requirements for the Use of Diesel-Powered Equipment in Underground Coal Mines; Proposed Rules. V. 54, No. 191, Oct. 4, 1989, pp. 40950-40997.
5. U.S. Department of Labor. Report of the Mine Safety and Health Administration Advisory Committee on Standards and Regulations for Diesel-Powered Equipment in Underground Coal Mines. 1988, 70 pp.
6. Federal Register. U.S. Mine Safety and Health Administration (Dep. Labor). Permissible Exposure Limit for Diesel Particulate. V. 57, No. 3, Jan. 6, 1992, pp. 500-503.
7. Waytulonis, R. W. The Effects of Maintenance and Time-in-Service on Diesel Engine Exhaust Emissions. Paper in Proceedings of the 2nd U.S. Mine Ventilation Symposium, University of Nevada-Reno, September 23-25, 1985.
8. Haney, R. A. 1992. Diesel Particulate Exposures in Underground Mines, Mining Engineering, 44(2):173-176 .
9. Cantrell, B. K., K. L. Williams, W. F. Watts, Jr., and R. A. Jankowski. Mine Aerosol Measurement. Chapter 27 in Aerosol Measurement: Principles, Techniques, and Applications, ed. K. Willeke, and P. A. Baron. Van Nostrand, 1993, pp. 591-611.
10. Liu, B. Y. H., K. Sega, K.L. Rubow, S.W. Lenhart and W.R. Myers. 1983. In-mask Aerosol Sampling for Powered Air Purifying Respirators, Am. Ind. Hyg. Assoc. J. 44:361-367.