Controls Being Used to Reduce Diesel Particulate Matter Exposures in U.S. Underground Metal and Nonmetal Mines

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Abstract

The U.S. Mine Safety and Health Administration (MSHA) conducted compliance assistance diesel particulate matter (DPM) sampling throughout the underground metal and nonmetal mining industry. Based on that sampling, MSHA identified mines that were having difficulty meeting the DPM limit. To provide further assistance, MSHA then visited approximately 60 of the mines that were experiencing difficulty complying with the DPM standard. As part of these visits, DPM exposures were measured and control technologies for DPM were observed and assessed. Controls consisted of ventilation, clean engines, environmental cabs, alternative fuels, diesel particulate filters (DPF), and work practices.

The focus of the follow-up compliance assistance visits was to assess control effectiveness and to make recommendations to mines experiencing difficulty in meeting the DPM standard. At each mine visited, the ventilation controls were evaluated, engine emissions were determined for equipment in use, environmental cabs were examined, and operational practices were noted. Additionally, control technologies, including alternative fuels and DPF, were evaluated in several mines.

A comparison was made of mine and section airflow to equipment particulate indices. Based on engine emissions, horsepower, and operating time, the contribution of individual engine emissions to total emissions was made. Environmental cab integrity, positive pressure, and air filtration systems were checked and operational practices relating to DPM exposure were assessed. The paper summarizes the preference and magnitudes of controls that were typically used or needed for successful control of DPM. Additionally, results of the assessments of alternative fuels (including bio-diesel and water emulsion fuels) and DPF are presented.

INTRODUCTION

On January 19, 2001 the Mine Safety and Health Administration published regulations to limit worker exposure to diesel particulate matter (DPM) in underground metal and nonmetal mines. As part of the regulation, the Agency reviewed the cost to the industry of implementing the regulation. Based on information supplied to the Agency by the mining industry, the Agency determined that the most cost-effective method of complying with the interim DPM limit used DPF along with cabs and ventilation upgrades. The final limit would be met through the use of additional, ventilation upgrades and a turn over in equipment and engines to less polluting models. As equipment was being replaced, new equipment would be equipped with environmental cabs. Mines should be adequately ventilated to prevent exposures to gaseous engine emissions.

Since that time, the mining industry has been working to implement controls that would reduce worker exposure to allowable limits. MSHA has supplied compliance assistance to the mining industry in three areas:

- The Agency conducted baseline DPM sampling in all of the underground metal and nonmetal mines;
- The Agency provided compliance assistance for developing a DPM control strategy for those mines where the interim 400_{TC} µg/m^3 limit (total carbon micrograms per cubic meter of air) was exceeded; and,
- The Agency conducted tests to assess the effectiveness of various controls for reducing DPM exposures.

The purposes of this report is to describe the types of engineering and work practices controls currently being used to limit diesel particulate exposures in underground metal and nonmetal mines and to summarize MSHA's compliance assistance efforts to help these mine operators develop control strategies for diesel particulate matter.

BACKGROUND

Between November 2002 and March 2003, MSHA conducted baseline diesel particulate sampling in underground metal and nonmetal mines. In all, approximately 875 samples were collected in 183 mines. This represented nearly all of the underground mines, as some mines are seasonally closed. Of those 183 mines, approximately 63 mines had at least one sample over the 400_{TC} µg/m^3 interim total carbon limit. MSHA Technical Support and Metal and Nonmetal Mine Safety and Health instituted a program to provide compliance assistance to each of the mines with an overexposure. This compliance assistance effort was initiated in May 2003. The Agency intends to continue this effort.

Of the 63 mines with one or more overexposures, 44 used room-and-pillar mining methods. These include, for example, stone mines, salt mines, and potash mines. Although trona mines use room-and-pillar mining methods, they were not visited because they were in compliance with the 400_{TC} µg/m^3 limit. The remaining 19 mines with overexposures were multilevel metal mines using a variety of stoping mining methods. Several industry seminars, as well as, specific mine visits have been conducted to assist these mines.

Typically, the high risk workers in the mines visited were the face workers that work outside an environmental cab. Production loader and truck operators had elevated exposures when they either did not have an environmental cab or when the cab was not being properly maintained. Additional high risk workers include the blasting crew, drillers, scalers and roof bolters.

During each mine visit, DPM samples were collected unless the mine had been recently sampled by MSHA, or the mine operator reported no additional DPM controls had been implemented since MSHA's previous sampling was completed. The visits also gave MSHA the opportunity to observe and evaluate the controls that were in place or being considered by the mining companies. DPM controls, including engines, ventilation, cabs, fuels, DPF, and work practices were reviewed with mine management. Specific engine emission rates, mine ventilation rates, cab pressures, and work practices were determined. At some mines a temperature trace of an engine exhaust was made.

RESULTS

Engines

During the past 15 years, great improvements have been made by diesel engine manufactures in reducing engine particulate emissions. The specific improvements included: turbo-charging, high pressure fuel injection, and computerized fuel injection. These changes have been primarily applied to direct injection engines. Prior to 1990, typical emissions for direct injection engines ranged from 0.5 to 0.7 grams per horsepower-hour (gm/hp-hr). For currently manufactured direct injection engines, the emissions range from 0.05 to 0.20 gm/hp-hr. Because of tighter emission standards, emission improvements have not been made to prechamber (indirect injection) engines. Emissions from prechamber engines have remained at 0.3 to 0.5 gm/hp-hr. Most of the mines visited are using loaders and haul trucks with new direct injection engines.

Most of the mines visited have or are in the process of upgrading their diesel equipment fleet to incorporate only clean burning engines. In many cases, engines with emissions less than 0.1 gm/hp-hr have been introduced into the mine. A number of mines that were having trouble meeting the 400_{TC} µg/m^3 limit had not upgraded their diesel fleet. The next major improvement to engine particulate emissions technology occurs in 2008 when U. S. Environmental Protection Agency (EPA) Tier 4 engines are phased in. These engines will have emissions less than 0.01 gm/hp-hr. This emission rate will be achieved through the application of diesel exhaust DPF.

Total contribution of diesel particulate to the mine atmosphere can be obtained by multiplying the emission rate by the horsepower and the hours of operation. A 300-hp, 0.10 gm/hp-hr engine, operated for 8 hours, produces approximately 240 grams of diesel particulate. This calculation was made for each of the engines in use at many of the mines visited during the compliance assistance effort. The calculation helps to identify the highest emitting engines and provides a rational basis as to which pieces of equipment should be replaced.

The highest emitting equipment was generally the production equipment (loaders and haul trucks) with high horsepower engines that operated for most of the shift. Loaders and haul trucks typically have space limitations in the engine compartment; as a result, it is usually not feasible to replace old engines in these vehicles with low emission engines. New loaders and haul trucks must meet EPA requirements for off-road vehicles and are typically equipped with clean burning engines.

Specialty mining equipment such as drills or roof bolters can be equipped with various engines. When ordering a new piece of equipment, a low emission engine should be specified. Because of the space available on this equipment, a high emission engine can typically be replaced with a low emission engine.

While loaders and haul trucks were generally identified as the highest contributor to DPM emissions, significantly higher emissions were noted on engines that were the old technology direct injection engines on trucks and loaders, or the prechamber engines on drills and roof bolters. Based on the observed engine use, a guideline of three strikes and replace the engine was developed. The three strikes are:

- High power (greater than 150 hp),
- High emissions (greater than 0.30 gm/hp-hr), and
- High utilization (greater than 6 hours per shift).

The introduction of clean burning engines has probably had the biggest impact on reducing DPM exposures. The change from engines with 0.3 to 0.5 gm/hp-hr emissions to engines with 0.05 to 0.15 gm/hp-hr has reduced exposures from 50 to 90%. Several mine operators reported that clean burning engines can reduce fuel usage up to 50%. As a result of reduced fuel consumption, the new engines can pay for themselves in two to three years.

The mine equipment maintenance is also an integral part of controlling engine emissions. Typically, mines performed a 250-hour preventative maintenance program. This included changing filters and fluids. More extensive maintenance was typically done by contractors. The two most significant maintenance factors effecting engine emissions are the intake air filter and the fuel injection rate. The intake air filter must be kept clean to avoid fuel rich combustion. Fuel rich combustion produced clouds of black smoke from the exhaust. An excess fuel injection rate, while providing more power, also produces increased particulate emissions. The fuel injection rate should not exceed the manufacturer's recommendation. To reduce particulate emissions, the fuel injection should be derated when the equipment has excess horsepower or when the equipment is operated at elevations above sea level per the engine manufacturers' specifications.

Ventilation

All mines recognized the importance and benefit of ventilation to dilute diesel particulate emissions. At many of the mines visited, efforts had been made to improve the mine ventilation system. These efforts included:

- Improved maintenance of existing airflow distribution systems,
- Installation of additional curtains to reduce short circuiting of airflow,
- Creating additional airflow openings to the surface,
- Repositioning of underground fans to improve local airflow distribution, and,
- Installing new fans or upgrading the capacity of existing fans.

The combination of improved ventilation with the significant reduction in engine emissions has resulted in a significant reduction in DPM exposures.

Mines were ventilated by either mechanical (fans and motors) or natural (temperature and elevation differences) ventilation methods. Typically, mines greater than 200 feet deep would use mechanical ventilation. Mines less than 200 feet deep would use either mechanical or natural ventilation. While temperature and elevation differences affect all mine ventilation systems, mechanical ventilation systems are characterized by the use of fans that maintain the same airflow direction year round. Natural ventilation enhances mechanical ventilation in the cold months and acts against the mechanical ventilation in hot months. Natural ventilation is neutral when the outside temperature is the same as the underground temperature.

Total airflow in the mines varied depending on the horsepower, types of engine and airflow distribution system. Historically, the recommended airflow to control gaseous emissions has been 100 cfm per horsepower (cfm/hp). This guideline was established prior to the development of clean burning engines. During the engine approval process, MSHA calculates a particulate index (PI). This is defined as the airflow needed to dilute the total particulate emissions to 1,000 $\mu g/m^3$. This value is equivalent to 800 $\mu g/m^3$ of total carbon. An airflow of double the PI would dilute the emissions to 400 $\mu g/m^3$ of total carbon. For engines that have been approved by MSHA, the particulate index can be found on the MSHA website. For engines not approved, the particulate index can be approximated from the formula:

$$\text{PI (cfm)} = \frac{\text{P (hp)} \times 0.55 \times 35{,}315 \times \text{E (gm/hp-hr)}}{60}$$

Where:

PI = particulate index in cfm,
P = rated engine power hp, and
E = engine power-specific emissions in gm/hp-hr.

For clean burning engines 0.05 to 0.20 gm/hp-hr, the PI ranges from 16 to 65 cfm/hp. Double the PI would range from 32 to 130 cfm/hp. Typical underground limestone mines utilize between 1,000 and 1,500 hp. The sum of the particulate indices typically ranged from 200,000 to 300,000 cfm. During the compliance assistance visits, it was observed that most mines that were successful in controlling diesel particulate were supplying a total mine airflow of double the sum of the particulate indices for all equipment used in normal operations. The airflow reaching the production areas was at least the sum of the PI for the equipment in operation.

The horsepower required to induce airflow through a mine can be estimated from the formula:

$$\text{Fan P (hp)} \sim \text{Q (cfm)} \times \text{H (in. w. g.)} / 5000$$

Where:
P = fan power in hp,
Q = the fan airflow in cfm, and
H = the fan pressure in inches of water gauge.

For an airflow of 250,000 cfm at 1 inch of water gauge, the power required would be approximately 50 hp. The pressure drop required to 250,000 cfm through a single 15-foot high by 36-foot wide entry is approximately 0.07 inches of water per 1000 feet (friction factor 80).

Because limestone, salt and potash mines have large openings or several openings for airflow, the mine resistance is low except for the airshafts. For a 10-foot diameter shaft, 100-foot deep and airflow of 200 000 cfm the pressure loss in the shaft would be approximately 0.2 inches of water gauge. However, for a 5-foot diameter shaft, the pressure loss would be approximately 6.4 inches of water gauge. The pressure loss is proportional to the shaft length and varies as the square of the airflow. A summary of pressure loss versus shaft diameter 100,000 cfm)of airflow through a 100-foot deep shaft are given in Table 1. Power varies as the cube of the airflow changes. Increasing the mine airflow by 25%, doubles the power cost required to move the air.

The amount of natural ventilation pressure (NVP) available to induce airflow through a mine can be approximated as 0.03 inches of water gauge per 100 feet of elevation change per 10° Fahrenheit temperature change. For underground stone mines, the elevation change is typically less than 200 feet and the inside to outside temperature variation is typically not more than 50° Fahrenheit. These factors indicate a normal NVP range of 0.30 inches of water gauge. There would be no NVP when outside and inside temperatures are the same. As a result, mines that are solely ventilated with natural ventilation will not be able to consistently comply with the diesel particulate matter permissible exposure limit (PEL).

For mines without main fans, in the summer when the inside temperature is cooler than the outside temperature, air will flow from the higher to lower elevation (cold air falls). In the winter when the inside temperature is warmer than the outside temperature, air will flow from the lower to higher elevation (warm air rises). For mines with main mine fans, the NVP assists the fan in the winter and opposes the fan in the summer.

In addition to inducing airflow into a mine, a system must be present to direct and distribute that airflow into the working areas of the mine. The type of air distribution system varied depending on the mine. Air walls of unexcavated rock or brattice lines are used to prevent short circuiting of airflow. Booster fans and auxiliary fans are used to distribute the airflow in the working areas. In mines with a flow through ventilation system (portal at the outcrop and shaft near the faces), the need for air walls for air distribution is reduced. Unfortunately, a number of mines utilized booster fans without a proper air distribution system. As a result, there was a perception of air movement, when the actual airflow was recirculated and fresh air was not being supplied to the working areas of the mine.

Significant contamination of intake air with diesel particulate contamination was observed at several mines where the intake and exhaust portals were located in close proximity. In these cases, the mine exhaust air was drawn back into the mine intake. To avoid this type of intake air contamination, intake and exhaust openings should be separated and placed a significant distance away from each other or a stack should be constructed to separate the two airflows.

Environmental Cabs

Most of the equipment being introduced into stone mines is equipped with environmental cabs. Environmental cabs are available for most of the equipment used in the evaporate (salt, trona, potash) mines and multilevel mines. Though their usage is increasing, they are not in widespread use in these industry sectors at this time. Environmental cabs are an effective means to reduce exposure not only to DPM but also to dust and noise. They can provide 60 to 80% reduction in DPM exposure for miners that remain inside a cab. Environmental cabs do not provide protection for downwind workers, whose work position is outside of an environmental cab. The noise, dust and DPM benefits of a cab can be fully realized only if the cab is sealed and pressurized to prevent inflow of contaminants and when the supplied and recirculated air are properly filtered.

An environmental cab is equipped with a pressurizing/filtration system. In order for the cab pressurizing/filtration systems to be effective, cab doors and windows must be closed and sealed. The pressurizer should provide one air change per minute 75 cfm for a 75 cubic foot cab. Both the intake and recirculation filters should be changed on a regular basis. Cab pressure should be at least 0.20 inches of water gauge. The pressure can be measured by placing a small hose through the cab door, closing the door, checking to make sure the hose is not pinched closed, and connecting the hose end to a portable water gauge. Typically, a gauge with a pressure range of 0 to 1.0 inches of water gauge is sufficient to measure the cab pressure.

The pressure measured on most cabs was less than 0.10 inches of water gauge. The low pressure was attributed to worn seals, dirty filters and hose conduit holes through the floor or body of the cab. Typically, the best environmental cabs were on the production loaders. However, because many of the loader operators are smokers, doors or windows are left open and the effectiveness of the cab is lost.

Over the road trucks (10 to 30 tons) typically have pressurizing systems but often do not have filtration systems. As a result, unfiltered air is drawn into the truck cab. A number of manufacturers supply after-market filtration systems that can be installed on truck cabs.

One problem specific to drill cabs was identified. Drill cabs are typically 200 cubic feet in volume (loader, haul truck, and scaler cabs are less than 100 cubic feet. When the original equipment manufacturer (OEM) has installed an after market pressurizer, the airflow capacity is typically 75 cfm. Cable and hose conduits are often run through the cab. As a result there is not enough airflow to pressurize the cab, resulting in cab pressures of 0.00. Additional pressurizing/filtration capacity should be added to large volume cabs and cab openings need to be sealed.

Alternative Fuels

The primary fuel in use by the underground mining industry is low sulfur, No. 2 diesel fuel (D2). Several types of alternative fuels are available to reduce diesel engine emissions. These include No. 1 diesel fuel (D1), bio-diesel blend fuels (either virgin soy oil or recycled vegetable oil), and diesel-water emulsion fuels. While available, these fuels are in limited use in underground mines. MSHA conducted compliance assistance visits to assess bio-diesel fuels and water emulsion fuels. Alternative fuel tests were typically conducted in limestone mines with shafts. This permitted the mine exhaust concentration and airflow to be monitored. Emissions were determined as the product of concentration and airflow. This permitted the evaluation of emission reductions to account for seasonal changes in mine airflow.

Table 2 summarizes the typical results of the various fuel tests. These results were confirmed by NIOSH in an isozone test conducted at a metal mine. In addition, NIOSH found approximately a 12% reduction in diesel particulate emissions could be obtained using a No. 1 diesel fuel.

For the bio-diesel fuel tests, equipment operators reported no noticeable loss of horsepower. However, the bio-diesel fuel acts as a solvent to clean the fuel system. As a result, a significant increase in maintenance was reported to replace clogged fuel filters. This increased maintenance subsided with the virgin soy oil but continued with the recycled vegetable oil. The bio-diesel fuel increases the fuel cost by $0.01 per gallon per percent of bio-diesel fuel. A 35% bio-diesel fuel increased the cost by $0.35 per gallon. The minimum effective bio-diesel blend was approximately 20% bio-diesel fuel.

As expected, when using fuels having 10 to 20% water content, equipment operators did report a noticeable loss of power. However, this power loss, even in the multilevel limestone mine, did not adversely effect production. In fact, during several of the mine tests, production was significantly above normal. The water emulsion fuel was favorably received by the employees. Workers reported that visibility improved. The water emulsion fuel has the same per gallon cost as No. 2 diesel fuel. Several operators reported as much as a 20% increase in fuel usage to compensate for the power loss.

Figure 1 shows a summary of the results of the alternative fuel tests conducted by MSHA. It also shows the results of tests conducted to evaluate No. 1 diesel fuel, a fuel oxygenator, environmental cabs and ceramic DPFs. All reductions are compared to diesel emissions with low sulfur No. 2 diesel fuel.

Work Practices

The MSHA regulation specifically eliminates worker rotation as an administrative control but permits other types of work practices as administrative controls. Several of these controls were observed during the compliance assistance visits. They include: hauling in exhaust airflow, drilling and shooting on separate shifts, keeping drillers and blasters upwind of production equipment, and limiting idling time. Hauling in exhaust air (the truck must have an environmental cab) prevents the truck exhaust from going to the production face. Additionally, establishing haulage travel ways in the intake and out the exhaust, can allow the trucks to generate a "piston" action which aids the ventilation.

Drilling and shooting on separate shifts allows these drillers and blasters, who often work outside a cab, from being exposed to emissions from production equipment. Similarly, keeping drillers and blasters upwind of production equipment keeps these workers from being exposed to emissions from production equipment. Limiting idling time reduces emissions that would have to be controlled by other methods.

Diesel Particulate Filters

None of the stone or evaporate mines visited during the compliance assistance period were using DPF. Currently, their use has been limited to multilevel metal mines. However, in order to reach the $160_{TC}\ \mu g/m^3$ level, many of the stone and evaporate mines will have to use DPF. Both MSHA and NIOSH tests conducted in metal mines showed that the ceramic DPF were better than 90% efficient for removing elemental carbon.

In order to have a successful DPF application, the engine duty cycle has to be matched to the DPF. The engine duty cycle can be quantified by taking a temperature trace of the engine exhaust. To obtain this temperature trace, a thermocouple with a datalogger is mounted in the exhaust pipe, as close to the engine manifold as possible. During the compliance assistance visits, temperature traces were made at most of the mines. These temperature profiles were obtained over a 4-hour period to demonstrate how to identify the equipment duty cycle. For actual DPF selection, the temperature profile should be made for several shifts to assure that normal operating conditions are observed. The information was downloaded into the NIOSH-developed spreadsheet to determine the 30% duty cycle temperature. This is the temperature that is exceeded by the engine 30% of the time. A plot of the temperature trace for a drill is given in Figure 2.

The 30% duty cycle temperature helps select the type of DPF that is best suited to an application. Passive regeneration occurs when the DPF becomes hot enough to burn off the captured diesel soot. Active regenerative systems can be on-board plug-in, removal of DPF and off-board cleaned in an oven, or an on-board fuel burning system. Before any filter selection is made, temperature traces should be made by the filter manufacturer to assure that the filter chosen is compatible with the application.

Typical guidelines for regeneration systems of filters are:

- T30% >550°C, Passive, Uncatalyzed "bare" trap,
- T30% >420°C, Passive, Base-metal catalyzed trap,
- T30% >365°C, Passive, Heavily Platinum-catalyzed trap,
- T30% >330°C, Passive, Lightly Platinum -catalyzed trap plus fuel borne catalyst,
- T30% <330°C, Active regeneration system.

The above temperatures are approximate; only the DPF supplier can properly make the recommendations. Also, when a DPF is installed, an exhaust back-pressure gauge should be installed to make sure the exhaust back-pressure does not exceed the engine manufacturer's recommendation. Regardless of the temperatures obtained during normal operation, some type of active regeneration system should be available in the event that soot accumulates in the filter during light duty cycle operations and needs to be removed.

At each of the mines visited, the requirements for passive and active regeneration were reviewed. It was recommended that older direct injection engines and prechamber engines be replaced rather than filtered. The amount of DPM collected in the DPF from these engines during operation is usually more than the amount of DPM that can be burned off during passive regeneration. If the DPM cannot burn off, the engine backpressure will continue to increase, which can lead to possible engine and/or DPF damage. The MSHA/NIOSH selection guide was discussed along with the best practices that are available on MSHA's website.

SUMMARY

The combination of improved ventilation with the significant reduction in engine emissions has resulted in a significant reduction in DPM exposures.

Clean burning properly maintained engines are an essential component of a DPM control strategy. Prechamber engines should be replaced and high-horsepower engines, that are used in production equipment, should have the lowest available emission engines.

Mechanical ventilation is required to consistently comply with the DPM limits. As a minimum, the ventilation system should induce twice the total equipment PI into the mine.

Properly designed and maintained environmental cabs significantly reduce DPM exposure for workers who can remain inside the cab.

Alternative fuels such as bio-diesel and water emulsions can provide more than 20% reduction in diesel particulate emissions.

Work practices can significantly lower exposures of workers who perform duties outside of environmental cabs.

DPF generally were not being used to comply with the 400 µg/m^3 limit; however, in many applications, DPF will be needed to meet the 160 µg/m^3.

Several general compliance strategies were observed. For the 400 µg/m^3 limit, mines have chosen to use clean engines, provide a minimum of the total PI as the mine ventilation quantity, use environmental cabs for mobile equipment operators and use work practice for workers who work outside of environmental cabs.

For the 160 µg/m^3 limit, mines indicated that they would supplement clean engines, environmental cabs and work practices with either 3 to 4 times the total PI as the ventilation rate or install DPF.

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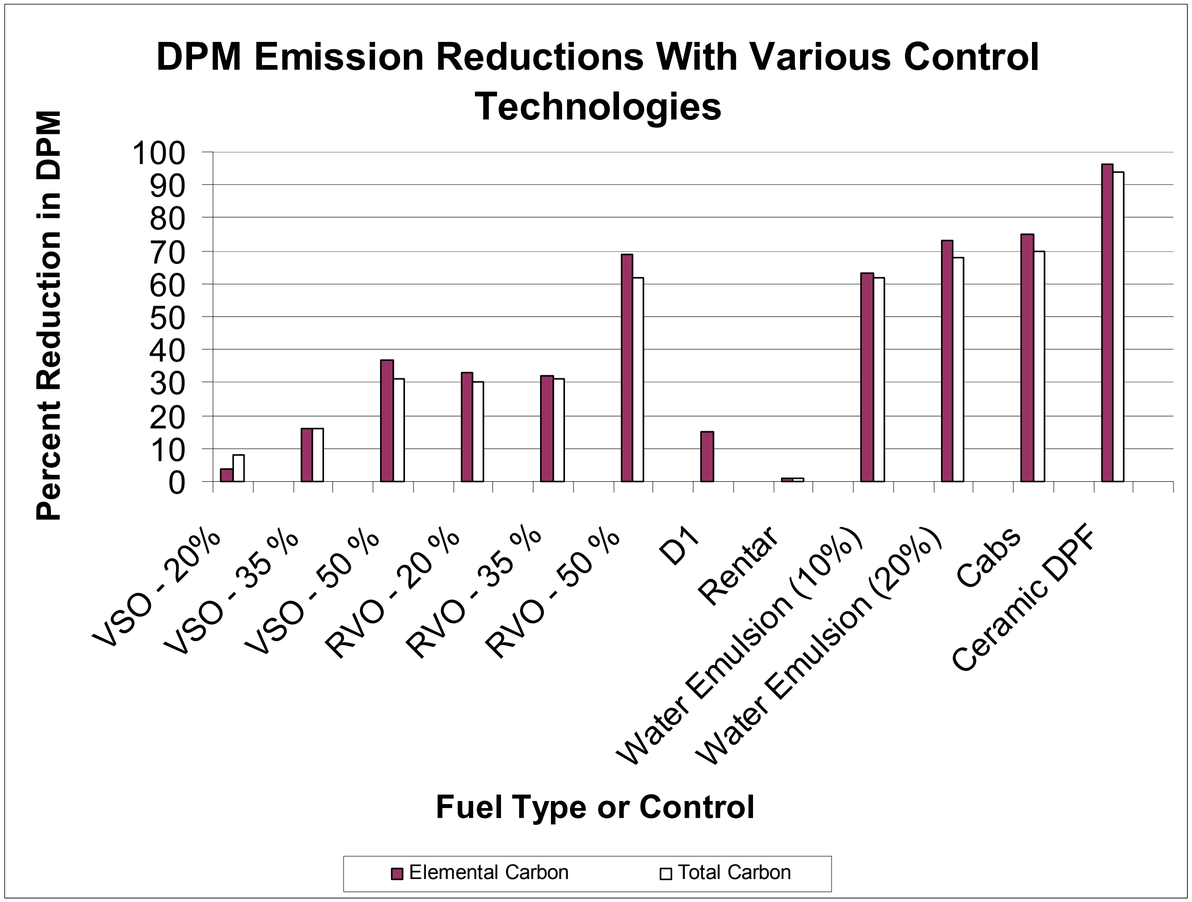
Table 1. Pressure Loss and Power Requirements for 100,000 cfm Flowing Through a 100-foot Deep Shaft (Friction Factor – 40).

Shaft Diameter Feet	Pressure Loss Inches of water gauge	Power Horsepower
4	4.87	98
5	1.60	32
6	0.64	13
7	0.30	6
8	0.15	3
9	0.08	2
10	0.05	1

Table 2. Percent reduction in diesel particulate emissions (Elemental Carbon) from baseline (No. 2 low sulfur diesel fuel).

Fuel Type	**Percent Reduction from No. 2 Diesel**		
Bio-diesel	**20% Bio-diesel Blend**	**35% Bio-diesel Blend**	**50% Bio-diesel Blend**
Recycled Vegetable Oil (RVO)	33	31	69
Virgin Soy Oil (VSO)	--	16	49
Water Emulsion Fuel	**Winter Blend**	**Summer Blend**	
	63	73	
D1	**Standard Blend**		
	12		



Notes: VSO – Virgin Soy Oil
RVO – Recycled Vegetable Oil
Rentar – Fuel Oxygenation System

Figure 1. Results of Field Studies on DPM Control Technology Effectiveness.

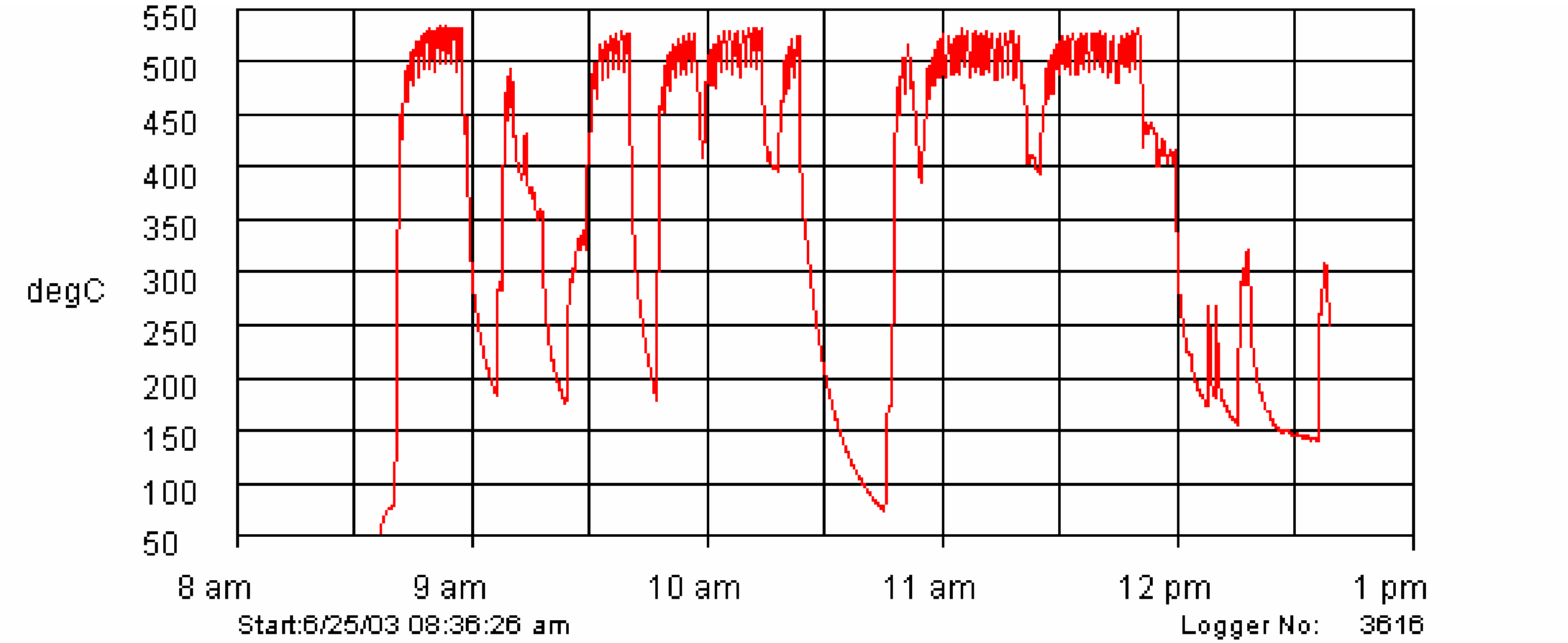


Figure 2. Temperature profile for a drill.