Novel Approach to Reducing Diesel Engine Emissions in the Mining Industry

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ABSTRACT

Part I:
The paper reviews the impact and potential benefits of a technology in which water is blended into diesel fuel to reduce exhaust emissions from diesel engines. The water blended diesel fuel used in this study, is co-developed by Caterpillar Inc. and The Lubrizol Corporation. It is known as PuriNOx™ Performance Systems and is currently under worldwide market introduction. "PuriNOx™" is a registered trademark representing a system that combines diesel fuel, water, and a proprietary additive package. A proprietary blending unit is used to produce a stable water/diesel blended fuel. PuriNOx™ fuel when compared to commercial diesel fuel, reduces NOx emissions up to 30% and particulate emissions up to 50%. The particulate matter reduction significantly improves the opacity of the exhaust. Specific emission improvements do depend on engine type. PuriNOx™ fuel is a *"fill and go"* product. In order to achieve the emission benefits of PuriNOx™ fuel no modifications to engine or fuel system are necessary. PuriNOx™ can provide emissions reduction for an existing base of diesel-powered vehicles. PuriNOx™ fuel is a blend of water, an additive system and regular diesel fuel. The water droplets are dispersed in the diesel fuel as a macro emulsion. The water improves the distribution of the fuel/air mixture within the cylinder of the engine, aids in the efficient combustion and lowers peak combustion temperature resulting in the emission benefits. The additive system keeps the emulsion stable and inhibits separation of the water from the diesel fuel.

Part II:
Clayton Group Services, Inc. (Clayton) performed air sampling studies at an Ohio salt mine, located in Cleveland, Ohio. The purpose of the study was to measure airborne diesel particulate matter concentrations prior to and subsequent to the introduction of PuriNOx™, a fuel additive intended to reduce diesel particulate matter emissions. The sampling was conducted on May 7 to10, and June 11 to 14, 2001. Two personal samples, three area samples, and two machine exhaust samples were collected each day during the study and analyzed for diesel particulate matter. Four days of sampling were conducted prior to, and four days subsequent to, the introduction of PuriNOx™. Sampling was performed so as to duplicate pre and post operations as closely as possible. By conducting a comparison of pre and post application of PuriNOx™ in the mine, results of the laboratory data and limited statistical analysis indicate a reduction in airborne diesel particulate matter concentrations after the introduction of PuriNOx™ of approximately 32%.

INTRODUCTION

Fuel efficient, heavy-duty diesel engines are the preferred power plants for commercial equipment, but they are also sources of air pollution. Based on experiments with animals and studies with workers exposed to diesel fuel, the Environmental Protection Agency (EPA) is expected to declare that diesel exhaust is a “likely human carcinogen.” The assessment will support efforts to further regulate emissions from diesel equipment.

An approach to reducing emissions of in-service diesel equipment that does not require engine modifications is the use of novel diesel fuel formulations. PuriNOx™ is a stable water-in-fuel emulsion comprised of No. 2 diesel fuel, water, proprietary additive, and seasonal components as needed. The fuel is produced in a highly automated, computerized blending unit fabricated to meet federal, state and local codes for safety and environmental protection. The unit contains its own spill containment, explosion proof controls, and water purification and can be placed at a fuel marketer, fuel distributor or end user site.

The water in PuriNOx™ fuel reduces NOx emissions by lowering the peak combustion temperature in the cylinder. Also, the water reduces PM by atomizing the diesel fuel through instantaneous vaporization. The visible opacity of diesel exhaust leaving a tail pipe is primarily made up of the carbon-core fraction of the particulate. PuriNOx™ preferentially reduces the carbon core fraction and thus almost 100% visible smoke reduction is possible. The emissions reduction with water-blended fuel is further enhanced with the use of exhaust after treatment, such as an oxidation catalyst.

This paper summarizes field tests that demonstrated emissions reductions in underground mining equipment. Clayton Group Services, Inc. (Clayton) conducted an air sampling study at the Cargill Salt Mines, located in Cleveland, Ohio. The purpose of the study was to measure airborne diesel particulate matter concentrations prior to and subsequent to the introduction of PuriNOx™, a fuel additive intended to reduce diesel particulate matter emissions. The sampling was conducted on May 7 to 10, and June 11 to 14, 2001, by Mr. Lee McKinney, Industrial Hygienist for Clayton, under the direction of Mr. Drew Carlson, Manager, Occupational Health & Safety for Clayton.

Two personal samples, three area samples, and two machine exhaust samples were collected each day during the study and analyzed for diesel particulate matter. Four days of sampling were conducted prior to, and four days subsequent to, the introduction of PuriNOx™. Sampling was performed so as to duplicate pre and post operations as closely as possible.

By conducting a comparison of pre and post application of PuriNOx™ in the mine, results of the laboratory data and limited statistical analysis indicate a reduction in airborne diesel particulate matter concentrations after the introduction of PuriNOx™ of approximately 32%.

Emission Test Definitions and Objectives

Clayton Group Services, Inc. (Clayton), conducted an air sampling study for airborne diesel particulate matter concentrations at the Cargill-Cleveland Salt Mines facility located in Cleveland, Ohio. Air sampling was conducted on May 7 to 10, and June 11 to 14, 2001, by Mr. Lee McKinney, Industrial Hygienist for Clayton, under the direction of Mr. Drew Carlson, Manager, Occupational Health & Safety for Clayton. The Clayton representatives were assisted by John Gruber, Mining Engineer, and Ron Richter, Mining Engineer (both with Cargill) to complete the scope of work.

The intent of the study was to gather air-sampling data from the Cargill-Cleveland Salt Mine facility to assess airborne diesel particulate matter (DPM) levels prior to and following the introduction of a diesel additive known as PuriNOx™ to vehicle fuel supplies, and subsequently compare results. The additive PuriNOx™ is a proprietary compound of Lubrizol and is intended to reduce DPM emissions. A limited comparison of sampling results was made against existing regulatory standards; however, the primary intent was to determine potential reduction in DPM concentrations after the introduction of PuriNOx™.

The objectives of the industrial hygiene assessment were to:

- Conduct air sampling on selected Cargill equipment operators to determine airborne DPM concentrations, focusing on underground operations, which presented potentially significant exposures.

- Conduct area air sampling to assess upstream and downstream DPM levels in the vicinity of the selected work area, and at an alternate downstream, exhaust point for the mine.

- Allow an interim period of four weeks for (1) the introduction of the PuriNOx™-containing fuel and (2) a subsequent atmospheric dilution period from the previous fuel mixture.

- Repeat the air sampling plan in a manner to duplicate as closely as possible the conditions that existed during the first sampling phase.

- Evaluate the laboratory data and conditions to determine the potential reduction in airborne DPM concentrations.

FACILITY AND PROCESS DESCRIPTIONS

General

The Cargill facility manufactures rock salt, predominantly for use as ice control on roads during the winter months. Some salt is further processed for agricultural and other purposes. The facility includes: (1) underground operations, which extract the rock salt from the subsurface, and (2) surface operations, which store, package, and transport the processed products.

The Cargill - Cleveland Mine surface operations include facilities for storage, packaging, and shipment of rock salt. Clayton did not conduct surface sampling as potential surface levels of DPM are readily diluted by natural ventilation and would not likely have produced results with statistical confidence.

The Cargill facility mines rock salt from the subsurface (below Lake Erie) at a depth of approximately 1,800 feet. The underground mine contains multiple tunnels and pathways where the underlying ore has been removed. Areas of study for this assessment included the ‘41/48’ Work Areas, and the area known as ‘Fault Hill’. The industrial hygiene assessment included monitoring of personnel (i.e., loader and scaler operators) and adjacent work areas.

Ventilation

The underground operations include two shafts (“Service” Shaft and “Production” Shaft) to facilitate transport of manpower, equipment, and ventilation to the underground areas. The Service Shaft introduces a continuous flow of ventilation into the mine and serves as the main entrance for workers to move between the surface and the underground areas. The Production Shaft is used to remove exhaust air from the underground areas and is used to hoist salt to the surface. The Production Shaft is also designated to transport personnel for certain emergency evacuation purposes.

The main fans circulate approximately 500,000 plus cubic feet per minute (cfm) of outdoor air to ventilate the mine. A “multi-pass” (or parallel) ventilation arrangement is used for the mine working panels, which allows separate splits of intake air to be delivered to each area. The ‘41/48’ mining panel is provided with 90,000 to 150,000 cfm of ventilation for continuous dilution and removal of generated air contaminants (i.e., diesel engine exhaust emissions) from employee working areas. The multi-pass ventilation arrangement prevents exhaust air from a mine panel from coming contact with employees at other mine working panels (in contrast to a “one-pass” [or series] ventilation system).

Underground operations are normally performed by 30 to 40 hourly personnel per workshift, including production miners, support miners, maintenance employees, supervisors, and other personnel. Production work may be conducted at two to three mine areas per shift. A typical work crew includes a mix of production and support miners (i.e. powderers, drillers, scalers, undercutters, haulage vehicle operators), mechanics, mill operator, belt crew employees, electricians, and salaried personnel. At the time of the sampling, employees were working 10-hour shifts, 4 days per week. Blasting operations were performed at the end of the afternoon shift, following completion of the sampling periods for this study.

Production Process (Mine Faces)

During sampling, ore extraction at the Cargill facility was performed at two locations (“41/48 Work Area,” “D North Work Area”) and was in preparation at a third work area (“2 North Work Area”). Each location contained multiple mine working faces. The ore is extracted from the mine faces by conventional mining techniques. The conventional mining operations include the following:

<u>Drilling</u> - The mine faces are hydraulically drilled with 2-inch diameter holes in preparation for powder loading work. This is accomplished through the use of diesel-hydraulic drilling machines. The work is completed by employees who spend the shift working at the mine faces.

<u>Undercutting</u> - The mine faces require additional preparation prior to powder loading through the use of an electric undercutting machine, in which the bottom section of the mine face is undercut in order to provide relief for blasting (i.e., the blasted ore falls in the correct sequence and in the intended areas).

<u>Powdering</u> - The drilled holes are pneumatically filled with an ammonium nitrate and fuel oil (ANFO) mixture. Each hole is primed with a non-electric blasting cap and a cap-sensitive primer. The work is completed by employees who work at the mine face(s) and operate diesel-powered vehicles to transport equipment to the working areas. Blasting is conducted using 12-foot advance cycles, or rounds.

<u>Blasting</u> - The ore is removed from the mine face through a controlled blasting sequence. This work is performed after completing the afternoon work-shift.

<u>Mucking</u> - Mucking involves the removal of blasted ore from the mine face and transporting the ore to a portable crusher by a load haul dump (LHD) vehicle and via multiple horizontal belt conveyor systems to move ore to the Mill Area.
LHDs move continuously between the mine faces and the nearest portable crusher feeder during the course of the workday.

<u>Scaling</u> - The roof (“back”) section of recently mined areas are “scaled” with diesel-powered scaling machines to prevent loose material from falling on workers. Employees performing this work spend the majority of the shift at the mine faces.

<u>Roof Bolting</u> - The roof (“back”) sections of recently mined areas are supported through the use of roof bolts to secure the salt to the overlying rock layers. The work is accomplished by a diesel-powered roof bolting machine. Employees performing this work spend the majority of the shift at the mine faces.

The ‘41/48’ Work Area was chosen for this study as an area of representative and full production. Mucking (loaders) and scaling operations were chosen as operations with the likelihood of higher DPM exposures than other operations, based on our previous experience with DPM samples at this location.

Because of the multi-pass system, other work areas and operations did not appear to have any significant impact on the ‘41/48’ work area chosen for this study, with the exception of a rehab bolter and waste haulage operations discussed in Section 5.0.

Other Functional Work Areas

The Main Gantry Area, used to repair and service mine equipment and vehicles is located upstream of the working mine faces. Air is introduced into the area by its own ventilation fan. The Mill Area, involved with processing of ore prior to hoisting to the surface, is located near the base of the Production Shaft, and is situated within the exhaust airstream of the mine ventilation system.

Neither of these areas appears to have any significant impact on the '41/48' work area chosen for this study. Additional transportation vehicles include John Deere "Gators" and Dodge Ram pickup trucks for personnel transportation. Usage was indicated as normal during the sampling periods.

STANDARDS AND GUIDELINES

The Mine Safety and Health Administration (MSHA) has recently (July 5,2001) established new health standards regarding employee exposure to DPM in underground non-metal mining facilities. The limits include the following:

- An "Interim Concentration Limit" (ICL) of 500 micrograms per cubic meter of air ($\mu g/m^3$) for DPM (or 400 $\mu g/m^3$ total carbon), expressed as an 8-hour time-weighted average (TWA), which will take effect July 19, 2002.

- A "Final Concentration Limit" (FCL) of 200 $\mu g/m^3$ for DPM (or 160 $\mu g/m^3$ total carbon), expressed as an 8-hour TWA, which will take effect January 19, 2006.

Both the MSHA ICL and FCL use the assumption that total carbon comprises approximately 80% of DPM found through previous studies completed by the National Institute for Occupational Safety and Health (NIOSH) and MSHA. These exposure limits must be adjusted for period exceeding the standard 8 hours per day and 40 hours per week.

METHODS AND MATERIALS

Air sampling was performed by drawing air through 37-millimeter (mm) diameter quartz fiber filters using battery-powered portable sampling pumps (MSA® Escort/Elf) at nominal flowrates of 1.7 liters of air per minute (Lpm). All sampling devices were calibrated against a Brooks sho-rate rotometer before and after each monitoring session. The rotometer was calibrated against a Gilian Gilibrator primary standard.

Personal sampling devices were affixed to the selected Cargill employees in the vicinity of their breathing zone. Flexible tubing, which connected the air inlet of the pump to the filter and cyclone device, was attached in a fashion to facilitate sample collection as close as possible to the employee's breathing zones.

The collected samples were analyzed at Clayton's American Industrial Hygiene Association (AIHA)-accredited laboratory in Novi, Michigan. Samples were analyzed according to NIOSH Method No. 5040 (Modified). The analytical instrument (Thermal Optical Analyzer) provided concentrations of organic carbon, elemental carbon, and total carbon (sum of elemental carbon and organic carbon) for each of the submitted samples. The NIOSH Method was modified by not using sub micrometer computer devices.

Blank samples were submitted for each type of air analysis for quality control purposes. Blank samples were added to the sample lot submitted to the laboratory to assess the potential for "background" contamination on the filter lots. The blank samples indicated that levels of total carbon were below the detection limit of 1 microgram [μg].

RESULTS AND DISCUSSION

The results of the industrial hygiene assessment of diesel engine exhaust emissions for the Cargill – Cleveland Mine facility are summarized below. All exposures are presented on an 8-hour TWA basis and assume equivalent exposure for any unsampled portion of the work period.

The sampling performed by Clayton focused on underground employees who operate vehicles / equipment powered by diesel fuel, and area samples. The '41/48' work area was specifically chosen as a significant production area for the purposes of this study.

A. Personal Samples

Two personal samples were collected each day for four days prior to, and subsequent to, the introduction of PuriNOx™. One sample each day was collected on a loader and scaler operator conducting routine mine face activity. For the purpose of this study and statistical confidence, these operations/machines appeared to present more significant DPM exposures.

B. Area Samples

Three (3) area samples were collected each day for four days prior to, and subsequent to, PuriNOx™ introduction. Theses samples were positioned upstream (entering) and downstream (exiting) the '41/48' work area; specifically, the upstream (intake) sample location was 55E and 32P, and downstream was 36 A and 35 P. An additional sample was collected at "Fault Hill," an area near the production shaft and representative of a whole mine exhaust point.

C. Machine Exhaust Samples

Two machine exhaust samples were collected each day for four days prior to, and subsequent to, PuriNOx™ introduction. These machines were being utilized in the '41/48' work area.

D. Discussion

Personal and area data provide the best statistical confidence because of the use of standard personal and area methodology. Machine exhaust emissions provide additional data, but method confidence is not as high due to factors related to machine maintenance, operating conditions, etc. Two data points were excluded in the machine exhaust samples due to significant variance of these data points to others, and due to the known mechanical issues of these machines ascertained during the course of sampling. Variance analysis of all data showed a before and after variance in the data of 0.114 and 0.115 respectively, suggesting the consistency and efficacy of the data, and sample collection and analysis.

Mathematical averaging of personal data reveals an average overall reduction of DPM before and after PuriNOx™ of approximately 30% reduction.

Averaging of area data reveals an overall reduction of DPM before and after PuriNOx™ of 31% reduction when including the intake/upstream data, and a 34% reduction not including intake/upstream data.

Averaging personal and area data combined show reductions of 30% with intake/upstream, or 32% without. Intake data for '41/48' showed a 7% increase in DPM, however, a rehab bolter and two waste haulage trucks were operating on the intake side of '41/48' after, but not before, the PuriNOx™ introduction phase. Because of this condition, it could be inferred that actual reduction percentages were higher. This would be only relevant in assessing reduction, and not for compliance exposure.

Machine exhaust samples show an aggregate reduction of 9%. Again, a greater variance in this data suggests less confidence in this sample collection technique.

Overall average reduction of all data before and after PuriNOx™ introduction is 21%.

Utilizing the higher confidence data (personal and area samples, discluding intake data), a reduction of airborne DPM concentrations is inferred from this data and analysis to be approximately 32%.

CONCLUSIONS

Clayton conducted DPM sampling at the Cargill - Cleveland Mine facility on May 7 to 10, and June 11 to 14, 2001 for determination of airborne DPM concentrations before and after the introduction of PuriNOx™. The sampling focused on conventional mining operations at the 41/48 Work Area and Fault Hill exhaust point.

PuriNOx™ water blended fuel was shown to improve DPM emissions compared to baseline fuel in Cargill Salt's mine that simulated typical driving conditions. The water-blended fuel required no engine or exhaust system modifications to achieve improved emissions. Laboratory results and data analysis suggest an overall DPM reduction of approximately 32%, based on testing condition differences in the pre- and post-testing phases, and reductions evident in higher confidence data.

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