DIESEL EMISSION CONTROL STRATEGIES AVAILABLE TO THE UNDERGROUND MINING INDUSTRY

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1.0 Introduction

The health effects of diesel emissions have received attention worldwide. Several organizations have been concerned about the health effects onroad diesel engines present for the general population. For example, a report in the December 1993 issue of *The New England Journal of Medicine* cited the significant health risk attributable to exposure to fine particulate material -- the materials characteristic of those emitted by diesel powered vehicles (ref. 1). More recently, a study published in *The American Journal of Respiratory and Critical Care Medicine* confirmed the findings of the earlier work (ref. 2). In 1988, the National Institute for Occupational Health and Safety categorized whole diesel exhaust as a probable carcinogen. Several other organizations, including the World Health Organization (WHO) in 1996 (ref. 3), the Health Effects Institute (HEI) in 1995 (ref. 4), and the International Agency for Research on Cancer (IARC) in 1989 (ref. 5), have published information on the potential adverse health effects of diesel emissions. Recently, the California Air Resources Board (CARB) classified diesel particulate as a toxic air contaminant.

Nonetheless for other reasons, the diesel engine remains an attractive option for powering heavy-duty onroad and nonroad vehicles. Vehicles are powered by diesel engines because: they are reliable, fuel efficient, easy to repair, and inexpensive to operate. Perhaps most impressive is the durability of the diesel engine. It is not uncommon for diesel engines to have a life of 1,000,000 miles in heavy-duty trucks, to power city buses for up to 15-20 years, and to power nonroad equipment for several thousand hours before requiring rebuild or replacement.

Because of its inherently better fuel efficiency, the diesel engine compares favorably with engines powered by gasoline and alternative fuels. Notwithstanding its problems with particulate emissions, the diesel engine has very low emissions of hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2), all of which pose risks to public health and the environment. For underground mine environments, the inherent safety of diesel fuel because of its relatively high flash point make it attractive for use in underground mines

Diesel emissions in underground mining environments have been recognized as a potential health threat for years. Initial concern about diesel emissions focused on control of CO and aldehyde emissions which were first controlled by diesel oxidation catalysts -- one of the first uses of diesel oxidation catalysts in the world. As the adverse health effects of diesel exhaust became more understood and the combined effects of the exhaust constituents on human health became more of a concern, CANMET contracted Ian W. French and Associates to look at the problem in more detail. This analysis resulted in the air quality index (AQI) as shown in equations 1:

$$AQI = \frac{CO}{50} + \frac{NO}{25} + \frac{DPM}{2} + 1.5\left[\frac{SO_2}{3} + \frac{DPM}{2}\right] + 1.2\left[\frac{NO_2}{3} + \frac{DPM}{2}\right] \qquad (1)$$

where; CO is carbon monoxide (ppm),
NO is nitric oxide (ppm),
NO_2 is nitrogen dioxide (ppm),
SO_2 is sulphur dioxide (ppm),
DPM is diesel particulate matter (mg/m3),
and the denominators are the individual constituent threshold limit values.

It was recommended that the AQI should not exceed a value of 3.

This initial work has resulted in the adoption of the Canadian Standards Association (CSA) standard CAN/CSA-M424.2-M90 for certification of underground diesel engines. Inspection of Equation 1 (the AQI) also shows that DPM is weighted quite heavily when considering the impact diesel emissions have on underground air quality.

To address the health concerns posed by diesel emissions, engine and control system manufacturers from around the world have been engaged in programs to develop, optimize, and demonstrate diesel emissions control devices, such as trap oxidizers, catalysts, and other newer emerging technologies. As a result, the cleaner diesel engine can be made available. Systems which combine catalyst or trap technologies with engine adjustments are emerging. One such technology has been demonstrated to provide a 42 percent reduction in nitrogen oxides (NO_x) emissions while maintaining very low particulate emissions. Substantial progress has recently been made in the development of lean-NO_x catalysts which can be used to significantly reduce NO_x emissions from diesel engines. It is expected that lean-NO_x catalysts will be commercially available soon. Selective catalytic reduction (SCR) systems have begun to see limited use in mobile source applications and with the introduction of electronic engines in underground mining applications, may find some application for mining vehicles.

Although not addressed in this report, the mining industry could look towards the use of cleaner alternative fuels and power sources to reduce miners' exposures to diesel emissions. In considering alternative fuels and power sources, the industry would have address the safety and infrastructure issues associated with some of these technologies. One alternative fuel which has found some use in the surface transportation sector and whose use has been demonstrated in the underground mining environment is a blend of biodiesel and standard commercially available diesel fuel. In the underground demonstration program, a 58 percent blend of biodiesel and D2 fuel was used in conjunction with oxidation catalysts (ref. 6). The study concluded that there was approximately a 20 percent reduction in diesel particulate emissions when the blended fuel was used.

2.0 Diesel Engines and Associated Emissions

2.1 Diesel Engine Operation

The diesel engine has been shown to be a reliable, robust power source for both onroad and nonroad vehicles. The diesel engine is relatively simple when compared to its gasoline counterpart and hence, is relatively easy to maintain. Unlike gasoline engines which depend on sparkplugs for ignition of the fuel, a diesel engine relies solely on the in-cylinder temperatures generated on the compression stroke for ignition of the injected fuel. Hence, the term compression ignition (CI). A requirement for proper combustion in a diesel engine is that it be operated lean, or with excess air in the combustion chamber, unlike the gasoline engine which is predominantly operated stoichiometrically, with the chemically precise amount of air in the combustion chamber to burn the injected fuel. In order to achieve the temperatures required to ignite diesel fuel in the combustion chamber, diesel engines are operated at high compression ratios -- typically in the range of 12 - 24 to 1 depending on the size and application. Diesel engines used in underground mining production vehicles operate at compression ratios in the range of 15 - 18 to 1 and can be considered medium speed, operating around 2,000 rpm. Smaller diesel engines, like those found in passenger cars, often operate at speeds in excess of 4,000 rpm. The very large diesel engines, like those found in marine vessels, can be operated at speeds as low as a few hundred rpm.

2.2 Types of Diesel Engines

Both direct injection (DI) and indirect injection (IDI) diesel engines are in use today. In IDI engine, fuel is injected into a precombustion chamber where combustion is initiated. As combustion proceeds, increased pressures in the precombustion chamber causes the combustion process to propagate into the main combustion chamber under well-mixed conditions where the process is completed and the power stroke begins. In DI engines, atomized fuel is injected at high pressures directly into the cylinder as the piston approaches top dead center (TDC) where it is combusted.

IDI engines have been used in closed environments like underground mines because of the lower levels of pollutants associated with them. However, IDI engines are less fuel efficient than DI engines. With recent advances in lowering the emissions from DI engines, their use is becoming more prevalent. IDI systems have traditionally been more popular on smaller diesel engines.

Diesel engines can be naturally aspirated or they can be turbocharged for increased power and performance. The increased power is a direct result of the combustion of more fuel which can be introduced into the cylinder because of the increased mass of air delivered to the cylinder as a result of turbocharging. Often air to air or liquid to air intercooling or aftercooling is provided on modern engines which helps reduce NO_x emissions.

Both two-stroke and four-stroke diesel engines exist. The two-stroke engine is more popular on smaller diesel engines because of its simplicity — it has fewer mechanical parts because of the nature of its inherent operation. Two-stroke engines deliver more power relative to their weight as compared to four-stroke engines, have been used extensively in the North American transit bus market, and can be found in underground mine vehicles. However, to a large extent, they are currently being replaced by four-stroke engines in both of these markets.

The difference between a two- and four-stroke engine lies in the number of times the piston travels between bottom dead center (BDC) and TDC to complete one combustion cycle. In a two stroke engine, the piston travels from BDC to TDC where combustion take place. As the piston returns to BDC, the exhaust gases are forced through an open exhaust port by the incoming fresh air charge. In a four-stroke engine, the exhaust gases are expelled from the engine in a separate complete cycle. As with the two stroke engine, the piston travels from BDC to TDC where combustion takes place. After the power stroke when the piston returns to BDC, the piston returns to TDC with the exhaust valve open expelling the exhaust gases. No combustion takes place on this stroke, and a fresh air charge is introduced into the cylinder for the next cycle as the piston returns to BDC.

Modern diesel engines have undergone a number of design changes in order to meet new U.S. environmental regulations. In particular, the new U.S. requirements for onroad diesel engines in 1991, 1994, and 1998 have resulted in design changes to reduce both particulate matter (PM) and NO_x emissions. Many of these design changes have been incorporated into nonroad diesel engines as well and will continue to be used as nonroad diesel engine standards are tightened in the U.S. Table 1 outlines typical heavy-duty engine specifications for diesel engines used in onroad vehicles. Classes IV through VII represent engines used in vehicles with a Gross Vehicle Weight Rating (GVWR) of 14,001 to 33,000 lb., such as school buses and delivery vans. Class VIII vehicles have a GVWR greater than 33,000 lb. Line haul transport trucks fall into this latter category.

Table 1: Typical HDD Engine Specifications Required to Meet Current Federal Standards

	Classes IV,V,VI,& VII	Class VIII
Combustion System		
# of Valves:	Generally 2	4 Preferred
Injector Offset:	<5% bore, <10E Preferred	<5% bore, <10E Preferred
Swirl:	Intermediate	Low
Combustion Chamber Bowl:	Re-Entrant	Open or Slightly Re-Entrant
Compression Ratio	16 to 17.5:1	15.5 to 17:1
K Factor Target	75%	75%

Table 1 (continued): Typical HDD Engine Specifications Required to Meet Current Federal Standards

	Classes IV,V,VI,& VII	Class VIII
Injection System		
Type:	Mechanical or Electronic Unit Injection, Hydraulically Actuated Electronic Unit Injection, or In-Line Pump	Electronic or Hydraulically Actuated Electronic Unit Injection
Maximum Pressure:	Up to 1300 bar	Up to 1600 bar
Timing Control:	Flexible Preferred	Flexible Preferred
Nozzle Type:	Minisac or Valve Covered Orifices	Minisac
Boosting System		
Type:	Turbocharged Aftercooled	Turbocharged Aftercooled
Aftercooler:	Air to Air	Air to Air
Oil Consumption	< 0.15%	< 0.15%
Oxidation Catalyst	Yes (Low Ratings)	No
EGR	No	No

Source: Needham (1995) (ref. 7)

2.3 Diesel Engine Emissions

Emissions from diesel engines include hydrocarbons (HC), carbon monoxide (CO), nitrous oxides (NO_x), and particulate matter (PM). Toxic compounds, like polyaromatic hydrocarbons (PAH), are also found in the exhaust of a diesel engine and can be associated with both the PM and HC emissions. Typical emissions from a diesel engine used in underground mining are shown in Table 2.

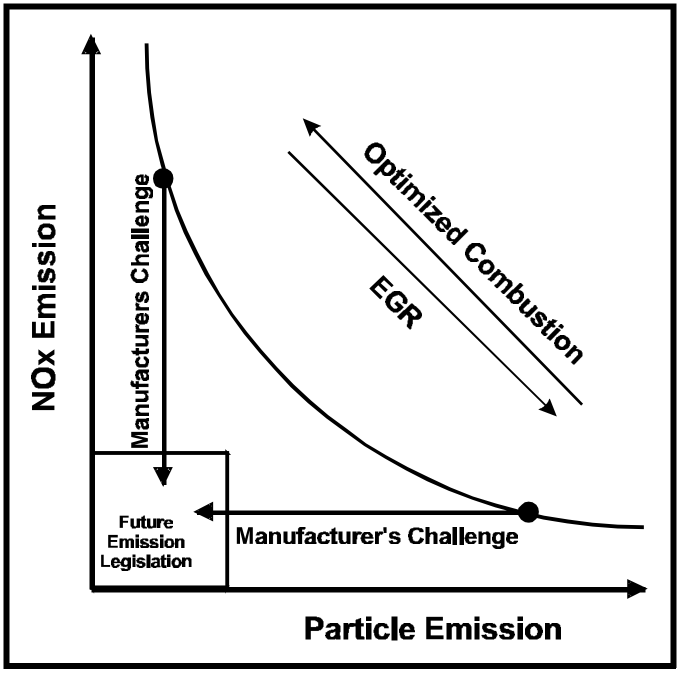
Table 2: 8-mode Emissions Data from a Deuitz BF 4M 1012C

CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	PM (g/kWh)
1.25	0.38	7.58	0.171

Source: Deutz Corporation, 1997 (ref. 8)

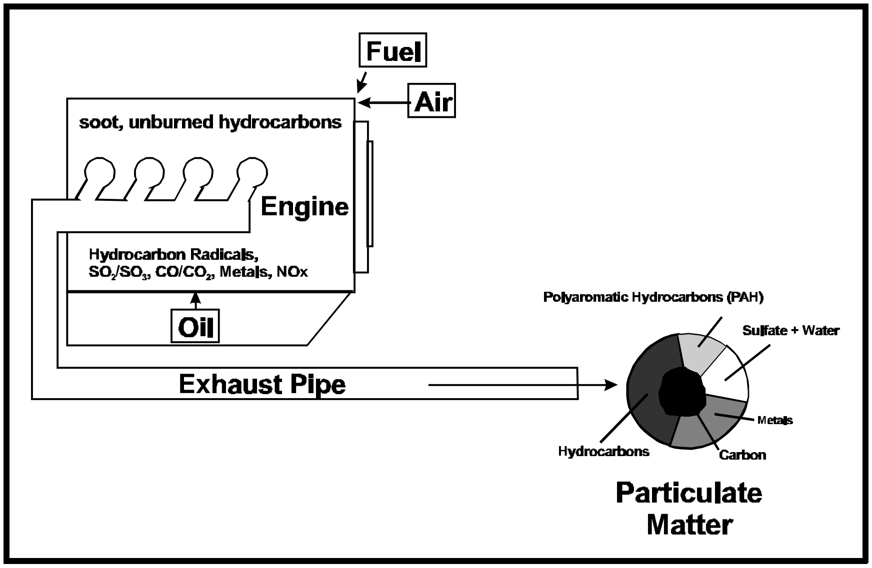
The nature of a diesel engine is such that many of the strategies used to minimize the in-cylinder formation of PM emissions will increase NO_x emissions because those strategies achieve more complete combustion and consequently result in higher in-cylinder temperatures. The formation of NO_x is solely a function of available oxygen and temperature. The trade-off is shown schematically in Figure 1 . This phenomenon presents an interesting dilemma to engine manufacturers when designing engines for very low levels of both PM and NO_x emissions.

Figure 1: PM/NO_x Tradeoff Associated with Diesel Engines



Diesel particulate matter is a complex substance. As shown in Figure 2, upon combustion of the fuel and lubricating oil found in the cylinder of a diesel engine, soot, hydrocarbons, wear metals, oxides of carbon, sulphur, nitrogen, and inorganic oxides exist in the cylinder. Diesel PM is formed through a combination of agglomeration, condensation, adsorption, changes to viscosity, and actual chemical transformations as the exhaust leaves the cylinder and travels along the exhaust pipe.

Figure 2: Diesel Particulate Matter Formation



3.0 Diesel Emission Control

Diesel engine manufacturers have made substantial progress in reducing engine-out emissions from diesel engines in response to stricter diesel emission control regulations worldwide. Furthermore, work continues by both engine and emission control manufacturers to develop technologies to further reduce emissions from diesel engines.

Diesel exhaust controls have been used on mining and material handling equipment for over 25 years to address occupational health concerns. Today, diesel exhaust emission control is occurring with other diesel engine applications worldwide.

3.1 Diesel Engine Design and Emission Reduction Advances

The 1990s have been a time for major technological advances to reduce emissions from diesel engines by diesel engine manufacturers. Driven first by the U.S. Environmental Protection Agency's 1991 requirement that diesel engines meet a PM emission standard of 0.25 g/bhp-hr combined with a 6.0 g/bhp-hr NO_x emission standard, and followed by the Agency's 1994 standard of 0.1 (0.05 for urban buses) g/bhp-hr for PM emissions along with a 5.0 g/bhp-hr NO_x requirement and the 1998 standard requiring that NO_x emissions be further reduced to 4.0 g/bhp-hr, engine manufacturers have focused on:

— improved fuel injection techniques,

— improved air management methods,

— improved combustion chamber design, and

— improved oil control.

3.1.1 Fuel Injector Design

Significant research and development has taken place on fuel injector design and placement to help manufacturers meet the U.S. onroad 1991 standards. Injector inclination, the number of holes and their diameters, sac volumes, and spray patterns have all been optimized for low emissions. Also in some instances, valve covered orifices (VCO) have been incorporated into injector designs to minimize residual fuel from entering the combustion chamber. Hydraulically-actuated electronic unit injectors have allowed manufacturers to control the rate of fuel injection which also has resulted in lower emissions of PM and NO_x for those engines which use them.

3.1.2 Fuel Injection Pressure

Increased fuel injection pressure has been used to increase atomization of the fuel in the combustion chamber, which in turn has resulted in lower PM emissions. Injection pressures in excess of 20,000 psi can be found on some diesel engines today. These engines are characterized by decreased swirl in order to minimize the NO_x formation which otherwise could occur due to the enhanced combustion resulting from the higher injection pressures. Manufacturers have had to make more robust fuel system components because of the increased pressures which has in turn increased the cost of the engines. Another strategy that has been used by manufacturers - especially manufacturers of lower cost light and medium heavy-duty engines - is using medium fuel injection pressure in combination with increased swirl.

3.1.3 Turbocharging and Air Cooling

A turbocharger is used to extract energy from a diesel engine's exhaust flow by using of an air compressor attached to an exhaust gas turbine located in the exhaust stream. The turbine is used to compress air to be fed to the intake air manifold. The increased mass of air to the combustion chamber allows for more fuel delivery and hence, increases engine power. Better combustion also results from turbocharging which in turn decreases PM emissions. Cooling the compressed air supplied to the intake air manifold reduces the NO_x emissions which otherwise would result from increased combustion temperatures.

In order to meet current onroad emissions standards, manufacturers have optimized turbocharger operation to match engine operating conditions more precisely, thereby avoiding over boosting which causes combustion to deteriorate, as well as making the turbocharger more responsive to transient conditions. Both of these techniques have resulted in lower PM emissions. Employing aftercooling, which results in lower combustion temperatures, has allowed manufacturers to optimize injection timing to minimize PM emissions while off-setting the increase in NO_x emissions that otherwise would occur.

3.1.4 Intake Manifold and Port Design

Intake manifolds and port configurations have been designed for better in-cylinder air distribution, eliminating fuel-rich spots. Rich areas during combustion result in incomplete combustion of some of the injected fuel and increase HC and PM emissions. The designs also insure proper fuel penetration into the cylinder and minimize cylinder wall wetting which both serve to decrease HC and PM emissions.

3.1.5 Combustion Chamber Design

Medium-duty diesel engines generally use re-entrant piston bowl designs. The re-entrant bowl causes in-cylinder turbulence and better fuel/air mixing. The better mixing improves combustion and decreases both PM and HC emissions.

3.1.6 Oil Control

Oil control on 1991 and newer onroad diesel engines has improved significantly compared to pre-1991 engines where as much as 30 percent of the PM emitted could be attributed to the combustion of lubricating oil (ref. 9). This improvement has decreased PM emissions by 10 percent.

3.2 Diesel Exhaust Emission Control Technologies

Diesel exhaust emission controls were first used in work environments when diesel oxidation catalysts were used in underground mines and on forklift trucks over twenty-five years ago, primarily for CO and HC control. Early on in the use of catalyst technology for diesel vehicles, manufacturers recognized the potential of catalyst technology to possibly increase the mutagenic activity of diesel exhaust. Consequently, attention was paid to properly formulate the catalyst to not only eliminate this potential but to reduce the mutagenic activity of the exhaust. More recently because of the U.S. EPA's urban bus rebuild/retrofit requirements for the reduction of diesel PM emissions, diesel oxidation catalyst technology has become recognized as an effective means of reducing PM emissions from diesel engines by greater than 25 percent.

In the late 1970s, considerable attention was given to the development of diesel particulate filter (DPF) technology, which was capable of reducing over 90 percent of diesel PM emissions. In 1986, the first diesel particulate filter systems were commercialized for underground production vehicles. Although the filters have seen limited use since first commercialized, their use has been highly effective where appropriately applied.

In the mid to late 1980s and into the 1990s with several regulatory initiatives underway in the U.S., emission control manufacturers have continued to refine and develop advanced diesel oxidation catalysts and filter systems. Also, much progress has been made in developing other advanced technologies like lean-NO_x catalysts and adsorbers among other technologies which will also play a role in reducing emissions from diesel engines. Applying traditional stationary source NO_x control technologies, like selective catalytic reduction (SCR), to mobile sources has begun.

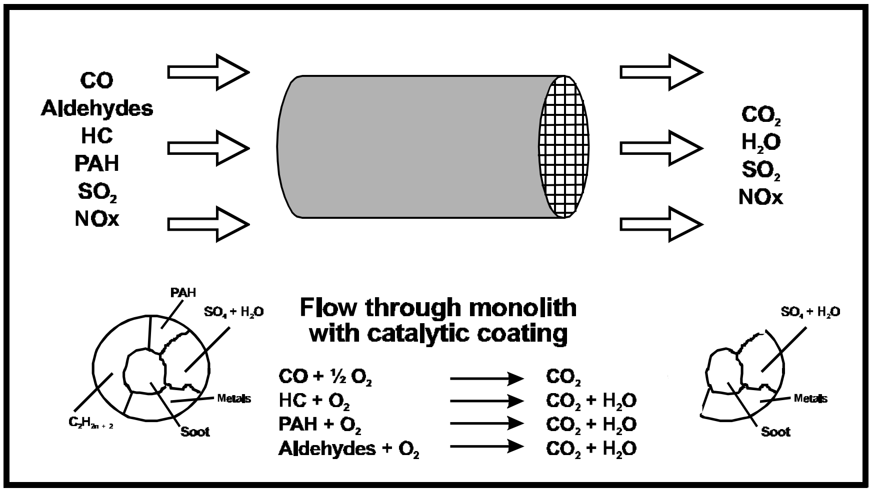
3.2.1 Diesel Oxidation Catalysts

3.2.1.1 Operating Characteristics and Control Capabilities

The concept behind an oxidation catalyst is that it causes chemical reactions without being changed or consumed. An oxidation catalytic converter consists of a stainless steel canister that typically contains a honeycomb-like structure called a substrate or catalyst support. There are no moving parts, just acres of interior surfaces on the substrate coated with catalytic precious metals, such as platinum or palladium. It is called an oxidizing catalyst because it transforms pollutants into harmless gases by means of oxidation. In the case of diesel exhaust, the catalyst oxidizes carbon monoxide (CO), gaseous hydrocarbons (HCs), and the liquid hydrocarbons adsorbed on the carbon particles. The liquid hydrocarbons are referred to as the soluble organic fraction (SOF) and make up part of the total particulate matter.

The operating principle of a diesel oxidation catalyst is shown in Figure 3.

Figure 3: Operating Principle of a Diesel Oxidation Catalyst

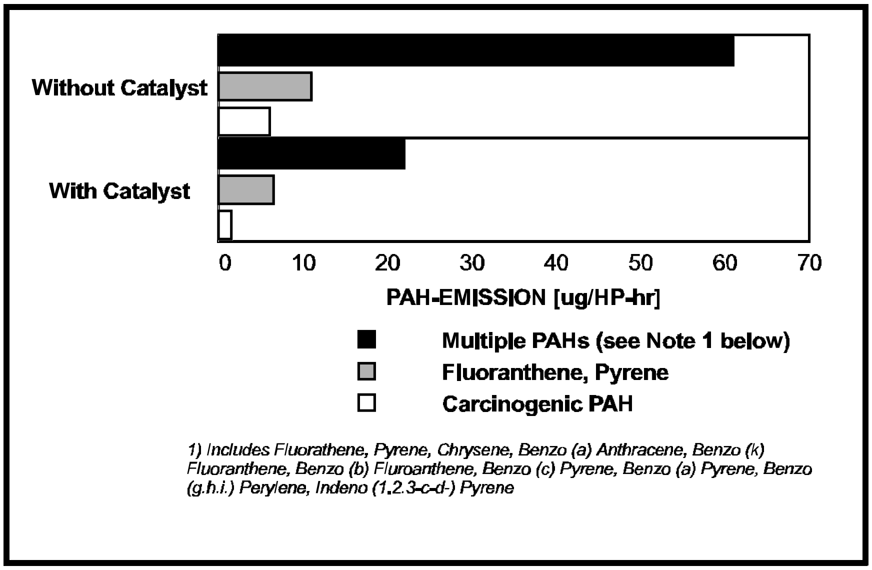


The level of total particulate reduction is influenced in part by the percentage of SOF in the particulate. For example, a Society of Automotive Engineers (SAE) Technical Paper reported that oxidation catalysts could reduce the SOF of the particulate by 90 percent under certain operating conditions and could reduce total particulate emissions by 40 to 50 percent (ref. 10). Destruction of the SOF is important because this portion of the particulate emissions contains numerous chemical pollutants that are of particular concern to health experts.

Oxidation catalysts are also effective in reducing particulate and smoke emissions on older vehicles. Under the U.S. EPA's urban bus rebuild/retrofit program, five manufacturers have certified diesel oxidation catalysts as providing at least a 25 percent reduction in PM emissions. The certification data also indicates substantial reductions in CO and HC emissions. A 1994 SAE paper reported that 120 buses in Argentina retrofitted with oxidation catalysts averaged over a 50 percent reduction in smoke opacity levels during a field demonstration (ref. 11). Although difficult to correlate these measurements to actual PM emission reductions, directionally the work would indicate some reductions.

Figure 4 illustrates the effectiveness of oxidation catalysts in reducing toxic emissions. As shown in the figure, all three of the PAH groupings measured were significantly reduced with the use of an oxidation catalyst over engine-out baseline emissions.

Figure 4: Effect of a Diesel Oxidation Catalyst on PAH Emissions



1) Includes Fluorathene, Pyrene, Chrysene, Benzo (a) Anthracene, Benzo (k) Fluoranthene, Benzo (b) Fluroanthene, Benzo (c) Pyrene, Benzo (a) Pyrene, Benzo (g.h.i.) Perylene, Indeno (1.2.3-c-d-) Pyrene

The sulphur content of diesel fuel is critical to applying catalyst technology. Catalysts used to oxidize the SOF of the particulate can also oxidize sulphur dioxide to form sulfates, which are counted as part of the particulate. This reaction is dependent on the level of sulphur in the fuel and also the temperature of the exhaust gases. Catalyst formulations have been developed which selectively oxidize the SOF while minimizing oxidation of the sulphur dioxide. However, the lower the sulphur content in the fuel, the greater the opportunity to maximize the effectiveness of oxidation catalyst technology. The low sulphur fuel (0.05% wt) which was introduced in 1993 throughout the U.S. has facilitated the application of catalyst technology to diesel-powered vehicles. Furthermore, the very low fuel sulphur content (<0.005% wt) available in several European countries has further enhanced catalyst performance.

Catalysts have also been effectively retrofitted to vehicles which run on fuel containing sulphur levels above 0.05% wt. Typical nonroad retrofit applications reduce PM, HC, and CO emissions when fuel containing 0.25% wt sulphur is used. In some instances, CO and HC emissions have been effectively controlled with sulphur levels as high as 0.5% wt. However, the performance of an oxidation catalyst in the presence of elevated fuel sulphur level is hard to predict since it will vary with catalyst formulation, engine type, and duty cycle.

3.2.1.2 Operating Experience

The diesel oxidation catalyst has become a leading diesel exhaust emission control strategy in both the onroad and nonroad sectors throughout the world, reducing not only PM emissions but also emissions of CO and HC. Using a flow-through oxidation converter on diesel-powered vehicles is not a new concept. Oxidation converters have been installed on nonroad vehicles around the world for over 25 years. From 1994 to 1998, over 1.5 million oxidation catalysts were installed on new onroad heavy-duty diesel engines in the U.S. and over 6 million passenger cars were equipped with oxidation catalysts in Europe.

Oxidation catalysts can play a significant role in removing particulate, smoke, and odor from existing diesel engines. Equipping oxidation catalysts on diesel engines is relatively straightforward. For example, in many applications the oxidation catalyst can be retrofitted as a muffler replacement. Indeed, many of the catalysts used on nonroad vehicles are retrofits, and recently, well over 10,000 oxidation catalysts have been retrofitted to urban buses and trucks in Europe and the U.S. The earliest installations have accumulated over 150,000 km and have proven to be virtually maintenance free.

On the nonroad side, oxidation catalysts have been used on diesel vehicles for over 25 years with over 250,000 installations completed to date. A significant percentage of these units have been installed on mining and materials handling vehicles, but construction equipment and other types of nonroad equipment have been retrofitted as well. PM emissions, as well as CO and HC emission reductions, are targeted in these industries for occupational health concerns. Typically, these systems operate trouble free for several thousand operating hours and are normally replaced only when an engine undergoes a rebuild.

Oxidation catalysts have also been used in other areas of the world for particulate control. In Chile, over 1,000 urban bus engines have been retrofitted with catalysts. In the Province of Mendoza, Argentina, 120 buses equipped with Mercedes Benz OM352 engines were retrofitted with catalysts. Over the six-month demonstration period, the buses in Argentina averaged a smoke opacity reduction of over 50 percent (ref. 11). Over 2,000 delivery trucks in Mexico have also been equipped with catalysts. Taiwan recently completed the initial phase of retrofit demonstration program which included the successful evaluation of catalyst technology retrofitted to diesel vehicles. Hong Kong has recently embarked on a retrofit program for urban buses where the criteria used is a 25 percent smoke reduction.

3.2.2 Diesel Particulate Filters

3.2.2.2 Operating Characteristics and Control Capabilities

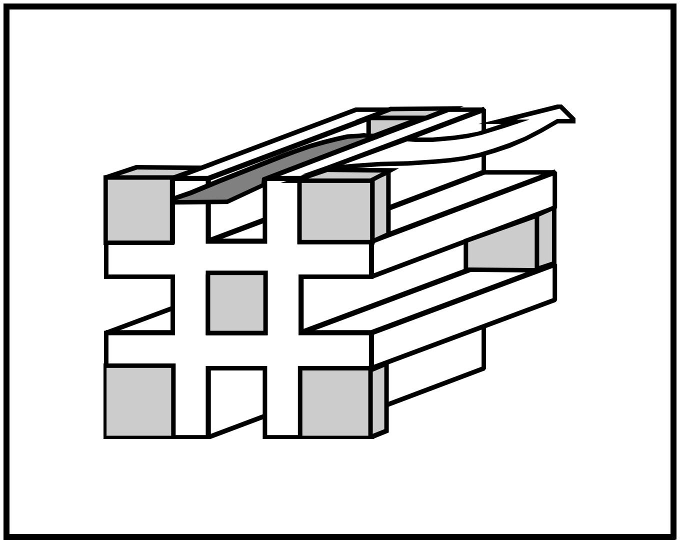
The trap oxidizer system consists of a filter positioned in the exhaust stream designed to collect a significant fraction of the particulate emissions while allowing the exhaust gases to pass through the system. Since the volume of particulate matter generated by a diesel engine is sufficient to fill up and plug a reasonably sized filter over time, some means of trapped particulate disposal must be provided. The most promising means of disposal is to burn, or oxidize, the particulate in the trap, thus regenerating, or cleansing, the filter. However, in nonroad applications there has also been use of a disposable filter system. The disposal filter is sized to collect enough particulate for a shift or two of operation while remaining within the engine manufacturers backpressure specification and then is removed and appropriately disposed of.

A complete trap oxidizer system consists of the filter and the means to facilitate regeneration if it is not of the disposable type.

Filter Material A number of filter materials have been tested, including ceramic and silica monoliths and fiber wound cartridges, knitted silica fiber coils, ceramic foam, wire mesh, sintered metal substrates, and temperature resistant paper in the case of disposable filters. Collection efficiencies of these filters range from 50 percent to over 90 percent. Currently, the ceramic monoliths, fiber wound cartridges, and paper filters have been used most extensively commercially. Silicon carbide is also beginning to be used commercially.

All of the filter technologies function in a similar manner; that is, forcing particulate-laden exhaust gases through a porous media and trapping the particulate matter on the intake side. Excellent filter efficiency has rarely been a problem with the various filter materials listed above, but work has continued with the materials, to: (1) optimize high filter efficiency with accompanying low back pressure, (2) improve the radial flow of oxidation through the filter during regeneration, and (3) improve the mechanical strength of the filter designs. Figure 5 shows an example of one type of filtration mechanism.

Figure 5: Diesel Particulate Filter



Particulate-laden diesel exhaust enters the filter, but because the cell of the filter is capped at the opposite end, the exhaust cannot exit out the cell. Instead the exhaust gases pass through the porous walls of the cell. The particulate is trapped on the cell wall. The exhaust gases exit the filter through the adjacent cell.

An SAE paper reported impressive results with an improved cordierite ceramic monolith filter (ref. 12). The newly designed filter achieved over a 90 percent particulate control efficiency while improving the coefficient of thermal expansion by 60 percent and the predicted thermal shock resistance by 200 percent over current filter designs. These significant improvements will enable the filters to withstand the rigorous operating conditions during planned, as well as unplanned, regenerations.

Regeneration The exhaust temperature of diesels is not always sufficient to initiate regeneration in the filter. A number of techniques are available to bring about regeneration of filters. It is not uncommon for some of these various techniques to be used in combination. Some of these methods include:

- Using a catalyst-coated filter. The application of a base or precious metal coating to the surface of the filter reduces the ignition temperature necessary for oxidation of the particulate;
- Using a catalyst to oxidize NO to NO_2 which adsorbs on the collected particulate, substantially reducing the temperature required to regenerate the filter;
- Using fuel-born catalysts to reduce the temperature required for the ignition of the accumulated material;
- Throttling the air intake to one or more of the cylinders, thereby increasing the exhaust temperature;
- Using fuel burners, electrical heaters, or the combustion of atomized fuel by catalyst to heat the incoming exhaust gas to a temperature sufficient to ignite the particulate;
- Using periodically compressed air flowing in the opposite direction of the exhaust flow to dislodge the particulate from the filter into a collection bag which is periodically discarded or burned; and
- Throttling the exhaust gas downstream of the filter. This method consists of a butterfly valve with a small orifice in it. The valve restricts the exhaust gas flow, adding back pressure to the engine, thereby causing the temperature of the exhaust gas to rise and initiating combustion.

The prime engineering goal of optimizing a filter system to a particular application is the elimination (or minimization) of any adverse effects of the system on engine or vehicle performance. Evaluations with filter systems development suggests these goals are attainable.

Non-catalyzed filter systems appear to have little or no effect on NO_x , CO, or HC emissions. Experience with the catalyzed filter system indicates that HC and CO emissions have been reduced considerably (in the range of 60-90 percent) with no adverse impact on NO_x

emissions. By using EGR and other approaches that rely on the NO_x-particulate matter tradeoff to control NO_x emission levels, the use of filter technology increases in its attractiveness.

Though difficult to quantify, one manufacturer has found that ceramic filters significantly reduce gas phase aromatics and noise (ref. 13). The experience with catalyzed filters indicates that there is a virtually complete reduction in odour and in the soluble organic fraction of the particulate, but some catalysts may increase in sulfate emissions. Companies utilizing these catalysts to provide regeneration for their filters have modified catalyst formulations to reduce sulfate emissions to acceptable levels. The low sulphur fuel (0.05% wt) currently available in the U.S. has greatly facilitated these efforts, although many other filter systems have operated successfully when used with higher fuel sulphur levels.

Filter systems which replace mufflers in retrofit applications have achieved sound attenuation equal to a standard muffler.

A very slight fuel economy penalty has been experienced with filter technology which is attributable to the back pressure of the system. Some forms of regeneration involve the use of diesel fuel burners, and to the extent those methods are used, there will be an additional consumption of fuel. It is expected that the systems can be optimized to minimize, or in some cases possibly eliminate, any noticeable fuel economy penalty. For example, in a demonstration program in Athens, no noticeable fuel penalty was recorded when the trap was regenerated with a cerium fuel-borne catalyst.

Trap systems do not appear to cause any additional engine wear or affect vehicle maintenance. Concerning maintenance of the trap system itself, manufacturers are designing systems to minimize maintenance requirements during the useful life of the vehicle. Various trap systems have been designed so that engine performance should have little or no adverse effects. Performance declines are minimized most notably by limiting back pressure.

3.2.2.2 Operating Experience

Trap oxidizer retrofit demonstration programs began in the 1980s and culminated in the early 1990s with the installation of almost 2,000 first generation systems in New York City on urban buses. The complexity of these first generation systems made reliability a problem which prompted manufacturers to develop the less complex more reliable systems mentioned above.

Development and commercialization of a number of second-generation trap systems capable of an 80 percent to greater than 90 percent PM emission reduction are underway. In Europe, diesel vehicles retrofitted with trap oxidizers are being offered commercially on a limited scale. Sweden's Clean Cities program has resulted in the commercial introduction of trap oxidizers on trucks and urban buses. Over 2,000 buses have been equipped with a passive trap oxidizer system with some of the buses having accumulated in excess of 250,000 miles. Sweden’s very low (<0.001% wt) fuel sulphur levels enables this technology to perform as designed.

Retrofit demonstration programs are currently being carried out in South Korea and Taiwan. In Taiwan, over forty buses have been equipped with ten different retrofit technologies including both catalysts and trap systems. Taiwan has plans to expand the demonstration to evaluate thirteen different retrofit technologies on ten buses each with a minimum mileage accumulation of 10,000 km. In Korea, over 200 trap systems were studied on truck and buses. The systems were evaluated for 50,000 km on the city buses and 20,000 km on the trucks with 0.15% wt sulphur initially in the diesel fuel. The fuel sulphur level subsequently changed to 0.10% wt.

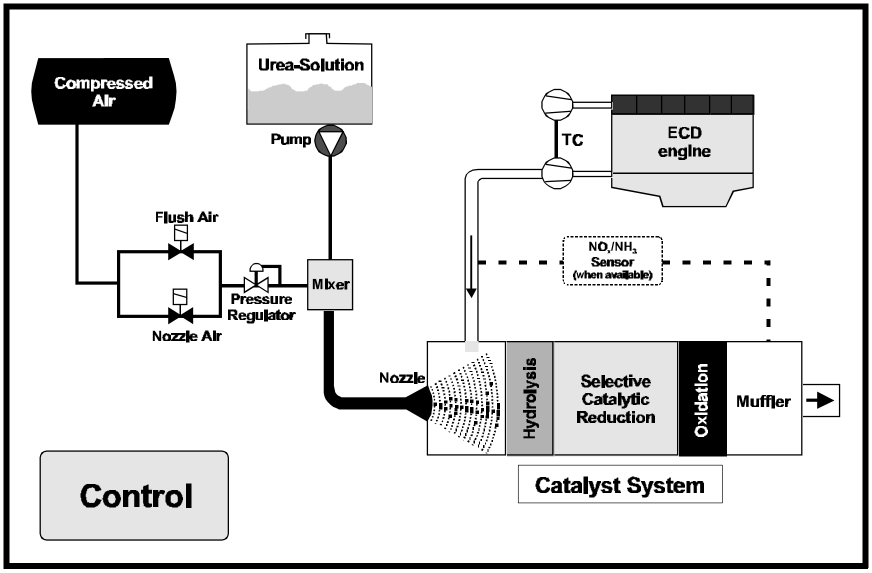
Filters have been commercially retrofitted to nonroad equipment since 1986 and currently, over 2,500 systems have been retrofitted and are in operation worldwide with some of the systems having operated for over 15,000 hours or over 5 years and are still in use. Both catalyzed trap systems and systems which are regenerated using factory shore power are in use in the nonroad sector.

3.2.3 Selective Catalytic Reduction (SCR)

3.2.3.1 Operating Characteristics and Control Capabilities

Like an oxidation catalyst, SCR causes chemical reactions without being changed or consumed. However, unlike oxidation catalysts, a reductant is added to the exhaust stream in order to convert NO_x to nitrogen and oxygen in what would otherwise be an oxidizing environment. The reductant can be ammonia, but in mobile source applications, urea is normally preferred. Figure 6 is a schematic of a mobile source SCR system.

Figure 6: Selective Catalytic Reduction



For proper operation of a SCR system, the reductant is added at a rate calculated from an algorithm which estimates the amount of NO_x present in the exhaust stream as a function of the engine operating conditions, e.g., vehicle speed and load. This insures minimal ammonia slip.

Where ammonia slip is a concern, an oxidation catalyst can be used to eliminate any trace amounts of ammonia coming through the system. As the exhaust gases along with the reductant pass over a catalyst applied to either a ceramic or metallic substrate, 75 to 90% of NO_x emissions, 50 to 90% of HC emissions, and 30 to 50% of PM emissions are reduced. SCR also reduces the characteristic odour produced by a diesel engine and the diesel smoke.

The catalyst composition of SCR and its mode of operation are such that the formation of particulate because of elevated fuel sulphur levels is not very significant. Even at temperatures in excess of 500ºC, only 5% of the sulphur in the fuel would be converted to sulfate which still allows for significant net PM emission reductions. Many of the systems in operation today are on sources which are powered by diesel fuel containing 0.3% sulphur by weight.

3.2.3.2 Operating Experience

SCR has been used to control NO_x emissions from stationary sources for over 15 years. Applying SCR to diesel-powered vehicles provides simultaneous reductions of NO_x, PM, and HC emissions.

SCR is currently being used on both onroad and nonroad vehicles. Highway trucks were first tested with SCR systems in 1994, and currently, 10 trucks are being demonstrated in Europe with the vehicles having accumulated over 160,000 km. The trucks range from 40 hp to 400 hp and the systems have been operating effectively throughout the demonstration. Recently, the demonstration was expanded to include an additional 12 vehicles.

SCR systems have also been installed on marine vessels and locomotives. Over 20 marine vessels have been equipped with SCR. The marine engines range from approximately 1250 hp to almost 10,000 hp, and the installations have been in operation since the early to mid-1990s.

3.2.4 Engine Treatments and Modifications in Combination with Exhaust Emission Control Technologies

3.2.4.1 Operating Characteristics an Control Capabilities

As previously indicated in Section 2.0, inherent to the operation and design of a diesel engine is a tradeoff between low PM emissions and low NO_x emissions. As engine manufacturers develop engines for MY 2004, employing strategies that reduce engine-out NO_x emissions, e.g., exhaust gas recirculation, in combination with exhaust emission control technologies to at a minimum offset what otherwise would be an increase in PM emissions is being seriously considered. Similarly, engines can be designed or calibrated for low PM emissions, e.g., advancing engine timing and technologies like SCR, or emerging technologies like lean-NO_x adsorbers can be used to offset what otherwise would be high NO_x emissions.

Several examples of combining engine modifications or treatments with exhaust emission control technologies have recently become commercial as a part of the U.S. EPA's urban bus rebuild retrofit program. These include:

- A kit recently submitted for certification for Detroit Diesel's DDEC II 6V 92 MY 1991 to 1993 engines uses a proprietary ceramic coating applied to the cylinder heads, valves, and piston domes along with a diesel oxidation catalyst certified for a 25 percent reduction under the urban bus program, rebuild components, and an improved turbocharger (The ETX kit). A similar kit was previously approved for Detroit Diesel's 6V 92 mechanical unit injector (MUI) MY 1979 to 1989 engines.

  The ETX kit relies on the proprietary engine coatings to enhance thermal management in the combustion chamber, thereby improving combustion efficiency and reducing particulate emissions. Particulate emissions are further reduced by the improved turbocharger because it increases the airflow. Subsequently, a catalyst is used to further reduce emissions.

- Another kit recently submitted for certification under the urban bus program for Detroit Diesel's DDEC 6V 92 MY 1985 to 1993 engines incorporates a propriety camshaft in combination with a diesel oxidation catalyst (CCT kit) and rebuild components. The kit was previously certified for MY 1979 to 1993 MUI engines.

  The CCT kit also uses a catalyst as a PM reduction strategy but further employs a proprietary cam shaft which is fitted to the engine at the time of rebuild. The cam shaft is used to increase the amount of time the combustion gases remain in the cylinder, thereby improving emissions.

- A third kit undergoing certification under the urban bus program uses an electronic supercharger in conjunction with a diesel oxidation catalyst and rebuild components for Detroit Diesel's 6V 92 MUI MY 1979 to 1989 engines. The PM emission reductions attributed to the use of the electronic supercharger result directly from the elimination of turbocharger lag during transient operation of the engine.

- A fourth kit upgrades the electronic control unit on Detroit Diesel's 6V 92 DDEC MY 1985 to 1993 engines in combination with a diesel oxidation catalyst and rebuild components. This technology relies on upgraded engine rebuild components along with upgraded electronic control of the engine along with the oxidation catalyst for low emissions.

Currently, seven applications have been made under EPA's urban bus program which combine engine modifications with exhaust emission controls to achieve a 0.1 g/bhp.hr PM emission standard.

Cummins Engine Company, as well as Detroit Diesel Corporation, have also certified rebuild kits which do not use exhaust emission controls to achieve PM emission reductions of 25 percent.

3.2.4.2 Operating Experience

The above technologies have been developed relatively recently and hence, have not received the in-use experience of some of the technologies mentioned in previous sections. Nonetheless, in-use experience is accumulating with over 500 systems having been installed on urban buses with some having accumulated upwards of 50,000 miles.

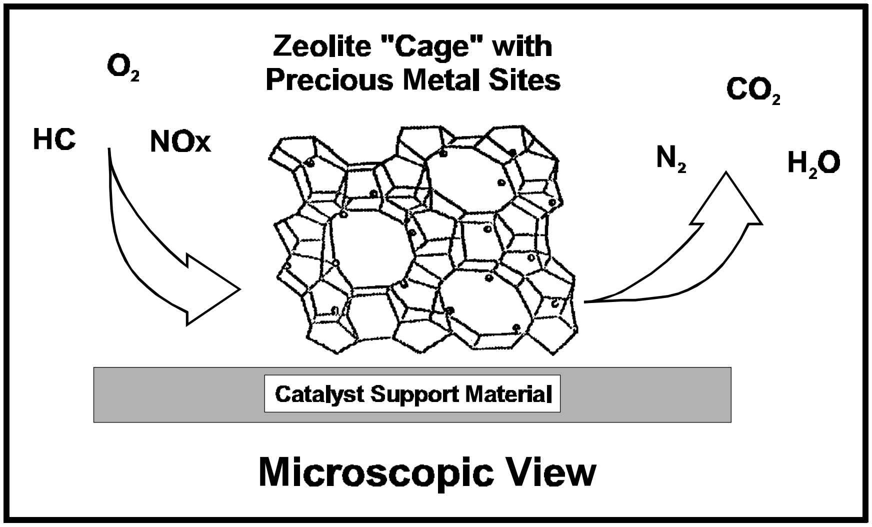
3.2.5 Lean-NO_x Catalysts

3.2.5.1 Operating Characteristics and Control Capabilities

While still a very new technology, considerable progress has been made in the field of lean-NO_x catalysts for diesel engines. The challenge in reducing NO_x emissions from diesel engines with a catalyst stems from the fact that the engines run lean, and hence, there is excess O_2 in the exhaust stream. However, the key to catalytically reducing NO_x emissions is a reducing, not an oxidizing reaction.

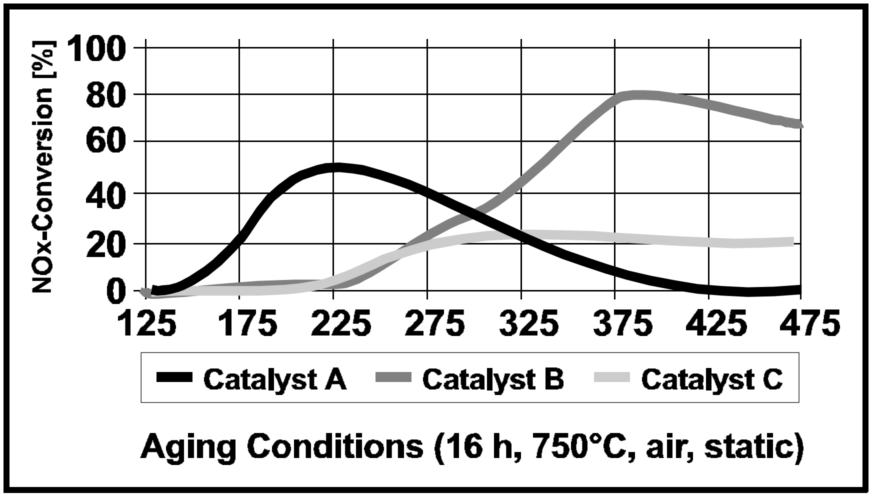
The first type of lean-NO_x catalysts developed employ base metals and/or precious metals contained on zeolitic structures. The zeolitic “cage” (as illustrated in Figure 7) acts to provide a local reducing environment, essentially creating a micro rich environment where the catalyst promotes the reaction of NO_x, HC, and CO to form N_2, O_2, and water.

Figure 7: Zeolite Lean-NO_x Catalyst



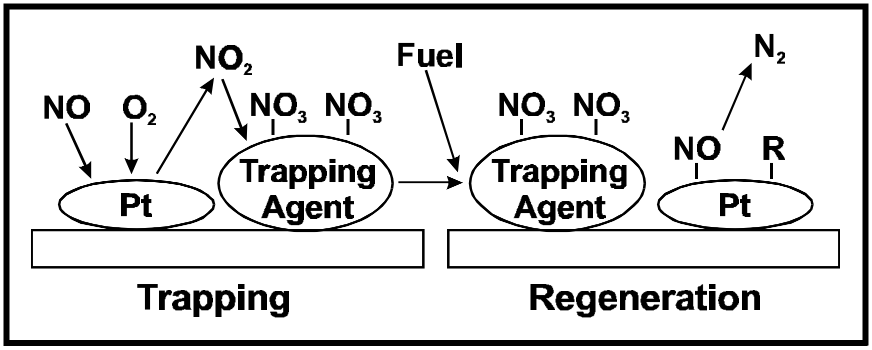
The capability of zeolite catalysts to remove NO_x emissions from diesels depends on the metals used, and it is a function of temperature. As shown in Figure 8, a combination of Catalyst A and Catalyst B would significantly improve the temperature window of these two experimental catalysts for NO_x control, making the combined system effective for NO_x control from approximately 175EC to over 475EC. Early work with zeolite catalysts showed that although promising reductions could be achieved initially as shown in Figure 8, performance dropped with aging. The performance of these catalysts have been found to be in the range of 15 to 20 % over driving cycles. This can be increased to 35 to 45 percent if fuel is injected into the exhaust stream in front of the catalyst. The amount of fuel injected is minimal and is expected to result in a fuel economy penalty of a few percent.

Figure 8: Performance as a Function of Three Lean-NO_x Zeolite Catalysts



More recently, development efforts by catalyst companies have focussed on lean-NO_x adsorber technology. Figure 9 schematically represents the mechanisms for NO_x reduction using adsorber technology.

Figure 9: Lean-NO_x Adsorber Technology



As indicated in the figure, the first step in the process is to convert NO to NO_2. The NO_2 then combines with the trapping agent (typically an alkaline metal) and oxygen to form metal nitrate. It is trapped there until a small quantity of fuel is injected upstream of the catalyst when the precious metal promotes the reaction between the trapped NO_x and the fuel to form nitrogen. It is anticipated that once fully developed, lean-NO_x adsorber technology will be capable of providing NO_x emission reductions in the range of 60 to 70 percent.

Lean-NO_x catalyst technology is sensitive to the level of sulphur in diesel fuel. In fact the levels of sulphur found in today's diesel fuel can be considered a barrier to the widespread use of the technology. Levels of sulphur well below 50 ppm would be preferred.

3.2.5.2 Operating Experience

Lean-NO_x catalysts have found limited use in direct injection gasoline-powered vehicles in Japan where very low sulphur levels are found in the fuel.

3.2.6 Other Upcoming Advanced Diesel Exhaust Emission Control Technologies

Two technologies that have received some attention recently for the reduction of diesel engines but have yet to see any real application, are flameless thermal oxidation (FTO) and plasma-assisted catalytic reduction of diesel PM and NO_x emissions.

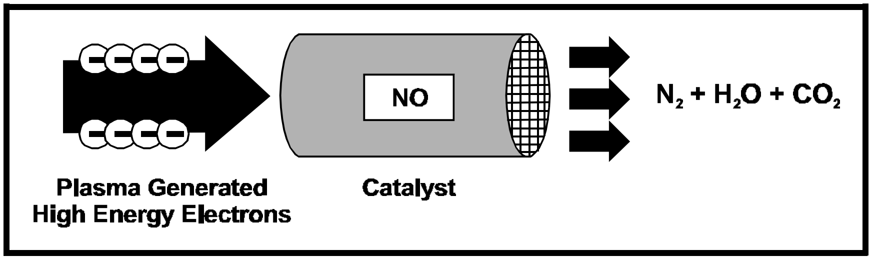
FTO technology has been used successfully in stationary source applications for control of volatile organic compounds (VOCs) with destruction efficiencies over 90 percent having been

manufacturer of a proprietary FTO system has indicated that the technology can be modified for use on diesel engines for the destruction of CO, HC, PM, and to some extent, NO_x

Plasma-assisted catalytic reduction of PM and NO_x
laboratory environments. The system employs plasma-generating electrodes mounted in a

catalyst they react with the exhaust emissions to produce N_2, O_2, and water. This is represented in Figure 10. Reductions of up to 80 percent in NO_x
reported. It is also reported that HC emission reductions are possible.

Figure 10: Plasma-Assisted Catalytic Reduction



refinement and optimization will be required before the technology can be considered commercially available.

3.2.7 Summary of Diesel Exhaust Emission Control Technologies

Table 3 summarizes the current state of the art of diesel exhaust emission control technologies.

Table 3: Summary of Diesel Exhaust Emission Control Technology

Technology	Control Capability (% Reduction)				Comments
	CO	HC	NO_x	PM	
Diesel Oxidation Catalysts	>90	>90	n.a.	>25	- proven technology - inexpensive - performance enhanced by low S fuel - reduces toxic emissions - watch for NO_2 formation
Diesel Particulate Filters	n.a.	n.a.	n.a.	>90	- has found use in mining for the right application - more expensive technology - can be catalyzed to reduce gaseous emissions - proper regeneration technique required
Selective Catalytic Reduction	>50	>70	80	>30	- recently applied to mobile sources - requires reagent - electronically controlled engines preferred - injection algorithms need to be developed
Lean-NO_x Catalysts Lean-NO_x w/HC-inj.	>70 >70	>70 >70	15-20 25-60	>30 >30	- still in the development stages, durability needs addressing - requires use of very low sulphur fuel
Lean-NO_x Adsorption	>70	>50	>70	>30	- still in the development stage - requires the use of very low sulphur fuel
Plasma-Assisted Catalytic Reduction	n.a.	n.a.	80	80	- still in the development stage - probably CO and HC reductions as well.
Flameless Thermal Oxidation	n.a.	n.a.	n.a.	n.a.	- stationary source technology being adopted to mobile source use - limited available data on emission reduction performance

n.a.- not available

4.0 Summary of Relevant, Worldwide Diesel Regulations

Outlined below are diesel emission regulations for a number of countries worldwide. Not only are underground mining regulations included, but relevant surface transportation regulations are included for the U.S. and European Union (EU) as these regulations will define the diesel engine technologies which will be available to the mining industry as the industry continues in its efforts to reduce underground miners' exposures to diesel emissions in the years to come.

4.1 Air Quality Regulations for Underground Mines

4.1.1 Summary of Worldwide Air Quality Regulations for Underground Mines

A number of countries around the world regulate air quality in underground mines. These regulations typically take the form of diesel engine tailpipe emission standards, ambient air quality standards, and/or fuel quality standards.

4.1.1.1 Diesel Engine Tailpipe Emission Standards

Tailpipe emission standards specify the maximum amount of pollutants allowed in exhaust gases discharged from a diesel engine. The regulated diesel emissions in underground mines include:

- carbon monoxide (CO);
- nitrogen oxides (NO_x), composed of nitric oxide (NO) and nitrogen dioxide (NO_2). Other oxides of nitrogen which may be present in exhaust gases, such as N_2O, are not regulated;
- smoke (opacity);
- diesel particulate matter (PM); and
- hydrocarbons (HC), regulated either as total hydrocarbon emissions (THC), as non-methane hydrocarbons (NMHC), or aldehyde emissions. One combined limit for HC + NO_x is sometimes used instead of two separate limits.

Emissions are measured over an engine or vehicle test cycle, which is an important part of every emission standard. Regulatory test procedures are necessary to verify and ensure compliance with the various standards. These test cycles are supposed to create repeatable emission measurement conditions and, at the same time, simulate a real driving condition of a given application. Analytical methods that are used to measure particular emissions are also regulated by the standard.

Regulatory authorities in different countries have not been unanimous in adopting emission test procedures, and many types of cycles are in use. Since exhaust emissions depend on the engine speed and load conditions, specific engine emissions which were measured on different test cycles may not be comparable even if they are expressed or recalculated into the same units of measure. This should be kept in mind whenever comparing emission standards from different countries.

Tailpipe emission standards are usually implemented by government ministries responsible for the protection of environment and/or occupational health, such as the Environmental Protection Agency (EPA) and the Mine Safety and Health Administration (MSHA) in the United States. The duty to comply with these standards is on the equipment (engine) manufacturer. Typically, all equipment has to be emission-certified before it is released in the market.

Table 4 summarizes the regulations for diesel engine tailpipe emission standards for underground mines in a few select countries.

Table 4 - Diesel Engine Tailpipe Emission Standards for Underground Mines

Country	Max. Allowable Concentration in Undiluted Exhaust			
	CO (ppm)	NO_x (ppm)	Smoke (Bosch Units)	PM (mg/m^3)
Canada[1]	2500	1500	NR	150
Germany[2]	500	750	3	NR
South Africa[2]	2000	1000	NR	NR
United States[3]	2500[a]	2000[a]	NR	NR
	3000[b]	2000[b]	NR	NR

Notes:
[a] standard for diesel-powered equipment for noncoal mines
[b] standard for diesel-powered equipment for gassy noncoal mines
NR: not reported

Sources:
[1] Gangal, Mahe. "Diesel Exhaust - Monitoring and Control." Presentation Given at American Industrial Hygiene Association Atlantic Provinces Section "Assessing and Regulating Hazards in the Mining Industry." Moncton-Dieppe, New Brunswick, November 19, 1996. (ref. 14)
[2] Sauerteig, Jaime. "Los Motores Deutz para uso en la Mineria Subterranea." Presentation Given at "El Motor Diesel en la Mineria Chilena" Seminar. Santiago, Chile, April 2-3, 1998. (ref. 15)
[3] Mine Safety and Health Administration. United States Code of Federal Regulations, 30 CFR § 75.1901. (ref. 16)

4.1.1.2 Ambient Air Quality Standards

Applications of diesel engines in confined spaces are regulated through occupational health and safety ambient air quality standards in addition to (or rather than) the tailpipe regulations. The ambient air quality standards specify maximum concentrations of air contaminants, called Permissible Exposure Limits (PELs) or Threshold Limit Values (TLVs), which are allowed in the workplace.

Gases found in diesel emissions, including carbon monoxide (CO), carbon dioxide (CO2), nitric oxide (NO), nitrogen dioxide (NO2), sulphur dioxide (SO_2), and many other compounds (e.g., aldehydes), have their PELs set by occupational health and safety authorities. Diesel particulate matter (DPM) has also been listed by a growing number of occupational health and safety standards as a toxic air contaminant.

These regulations are set and enforced by occupational health and safety authorities such as OSHA (Occupational Safety and Health Administration) and MSHA in the United States. The duty to comply is the responsibility of the end-user (e.g., mine operator, etc.) who has to make sure that the emission control measures which have been employed are adequate to the type and number of polluting equipment. Engine or equipment manufacturers do not have any direct obligations in regard to the occupational health and safety air quality standards.

Table 5 summarizes the requirements for ambient air quality in underground mines.

Table 5 - Ambient Air Quality Regulations for Underground Mines

Country		Maximum Allowable Concentration (ppm)						
		CO	CO_2	NO	NO_2	SO_2	Diesel Particulate (measured as RCD) (mg/m^3)	Total RCD (mg/m^3)[a]
Canada[5]	Federal	25	5000	25	3	2	1.5	3
	Alberta	25	nr	nr	3	2	nr	nr
	British Columbia	25	nr	nr	3	2	1.5	nr
	Manitoba	25	nr	nr	3	2	nr	3
	New Brunswick	50	nr	nr	3	2	1.5	nr
	Newfoundland	25	nr	nr	3	2	nr	3
	Northwest Territory	50	nr	nr	3	2	nr	3
	Nova Scotia	50	nr	nr	5	5	nr	nr
	Ontario	35	nr	nr	3	2	1.5	5
	PE	25	nr	nr	3	2	nr	3
	Quebec	35	nr	nr	3	2	nr	nr
	Saskatchewan	25	nr	nr	3	2	nr	3
	Yukon Territory	50	nr	nr	5	5	nr	nr
Germany[4]		NR	NR	NR	NR	NR	NR	0.3[b,c]
		NR	NR	NR	NR	NR	NR	0.1[b,d]

Table 5 (continued) - Ambient Air Quality Regulations for Underground Mines

Country	Maximum Allowable Concentration (ppm)						
	CO	CO_2	NO	NO_2	SO_2	Diesel Particulate (measured as RCD) (mg/m^3)	Total RCD (mg/m^3)[a]
South Africa[2]	100	5000	NR	5	NR	NR	NR
United States[4]	50[e]	5000[e]	25[e]	5[e]	2[e]	NR	NR
	50[f]	5000[f]	25[f]	5[f]	5[f]	NR	NR

Notes:
[a] respirable combustible dust
[b] as colloid dust (colloid dust is defined as that part of total respirable dust in a workplace that passes the alveolar ducts of a worker)
[c] for non-coal underground mining and construction work
[d] for all other mining in workplaces
[e] for coal mines
[f] for metal/nonmetal mines
nr: not regulated
NR: not reported

Sources:
[2] (ref. 15)
[4] Mine Safety and Health Administration. "Diesel Particulate Matter Exposure of Underground Coal Miners; Proposed Rule." Federal Register. Vol. 63, No. 68. Pgs. 17492-17579. April 9, 1998. (ref. 16)
[5] Fact Sheet for Mine Health and Safety Activists: Diesel Exhaust Exposure Limits. (ref. 17)

4.1.1.3 Diesel Fuel Quality Standards

Flash point, sulphur content, and cetane number are properties most frequently specified in fuel quality requirements. The flash point is the temperature at which the quantities of vapor that the diesel fuel emits into the adjoining atmosphere are sufficient to allow a spark to ignite the vapor-air mixture above the fuel. Most countries have transportation and storage safety considerations which dictate that diesel fuels have a flash point above 55EC. The sulphur content shows the maximum sulphur level by weight allowed in the fuel. Besides the major health concerns and adverse environmental effects caused by sulphur dioxide (created by the combustion of sulphur), sulphur in diesel fuel also diminishes the effectiveness of catalytic converters installed on diesel engines. The cetane number expresses the diesel fuel's ignition quality. The higher the cetane number, the greater the fuel's tendency to support self-ignition. A cetane number of 50 or higher is desirable for optimal operation in today's diesel engines.

Table 6 summarizes the fuel quality requirements for diesel engines in underground mines.

Table 6 - Diesel Fuel Quality Requirements for Underground Mines

Country		Min. Flashpoint (EC)	Max. Sulphur Content (%)	Min. Cetane Number
Canada[1]	National	40 (regular)[a] 52 (special)[a]	0.5 (regular)[a] 0.25 (special)[a]	NR
	Alberta	40 (regular)[a] 52 (special)[a]	0.5 (regular)[a] 0.25 (special)[a]	NR
	British Columbia	52 (special)[a]	0.25 (special)[a]	NR
	Manitoba	40 (regular)[a] 52 (special)[a]	0.5 (regular)[a] 0.25 (special)[a]	NR
	New Brunswick	NR	NR	NR
	Newfoundland	40 (regular)[a] 52 (special)[a]	0.5 (regular)[a] 0.25 (special)[a]	NR
	Northwest Territory	52	0.25	NR
	Nova Scotia	52	0.25	NR
	Ontario	52	0.25	NR
	Quebec	NR	0.25	NR
	Saskatchewan	52	0.5	NR
	Yukon Territory	52	0.25	NR
United States[3]		38	0.05	NR

Notes:
[a] current CAN/CGSB-3.16-M86 standard on Mining Diesel Fuel.
NR: not reported

Sources:
[1] (ref. 14)
[3] (ref. 16)

4.1.2 Air Quality Regulations for Underground Mines in the United States

The Mine Safety and Health Administration (MSHA) is the regulatory agency which oversees air quality and safety concerns in underground mines in the United States. It is the task of the agency to set the emission control requirements for the primary exhaust pollutants emitted from diesel-powered engines.

On October 25, 1996, MSHA issued a final rule which established new requirements for (1) the approval of diesel engines and other components used in underground coal mines, (2) the monitoring of gaseous diesel exhaust emissions by coal mine operators, and (3) safety standards for the use of diesel-powered equipment in underground coal mines. The final rule is derived in part from existing MSHA regulations and provides protection against explosion, fire, and other safety and health hazards related to the use of diesel-powered equipment in underground coal mines. The final rule also amends certain equipment safety standards previously applicable only to electric-powered equipment to apply to diesel-powered equipment.

On April 9, 1998, MSHA proposed a rule designed to reduce the risks to underground coal miners from serious health hazards that are associated with exposure to high concentrations of diesel particulate matter (DPM). Underground miners are exposed to far higher concentrations of DPM than any other group of workers. According to MSHA, evidence indicates that such high exposures put these miners at excess risk to a variety of adverse health effects, including lung cancer.

The proposed rule would require that all permissible and heavy-duty nonpermissible diesel-powered equipment be equipped with a filtration system that is capable of removing, on average, at least 95% by mass of the particulate emissions. Following 18 months of education and technical assistance by MSHA, filters would first have to be installed on permissible diesel-powered equipment. By the end of the following year (i.e., 30 months after the rule is issued), filters would have to be installed on any heavy-duty nonpermissible equipment. No specific concentration limit would be established in this sector; the proposed rule would only require that filters by installed and properly maintained. The rule would also require that the mine's ventilation and dust control plan contain a list of the diesel-powered equipment used in the mine and filtration system installed on each. Miner awareness training on the hazards of DPM would also be required.

The proposed rule builds on existing underground mining regulations intended to reduce harmful DPM emissions from diesel-powered equipment. These regulations include: 1) a requirement that only low-sulfur diesel fuel be used underground, 2) restrictions on the idling of diesel-powered equipment, 3) ensuring that maintenance of diesel-powered equipment is performed only by qualified personnel, 4) weekly tailpipe tests to ensure the engines are operating in approved condition, and 5) the requirement that the entire diesel fleet have approved engines before the year 2000.

In the near future, MSHA intends to propose a separate rule to reduce DPM exposures in underground metal and nonmetal mines.

4.2 United States Environmental Protection Agency (U.S. EPA)

The U.S. EPA has recently adopted new regulations for heavy-duty diesel engines for both the on- and nonroad sectors. Currently, EPA is performing a technology review of both the on- and nonroad rules. The onroad technology review is to be completed in 1999 while the nonroad review is scheduled for completion in 2001. In the reviews, EPA is looking at the feasibility for manufacturers to meet the standards, the feasibility to meet tighter standards, and the applicability of the steady state test procedure for nonroad engine certification.

Table 7 and 8 outline EPA’s on- and nonroad standards.

Table 7: U.S. Onroad Heavy-Duty Engine Emission Standards

	Year	HC (g/bhp-hr)	CO (g/bhp-hr)	HC + NO_x (g/bhp-hr)	NO_x (g/bhp-hr)	Diesel Particulate (g/bhp-hr)
Diesel	1991-1993	1.3	15.5		5	0.25
	1994-1997	1.3	15.5		5	0.1
	1998	1.3	15.5		4	0.1
	2004	1.3	15.5	2.5		
Urban Buses	1991-1992	1.3	15.5		5	0.25
	1993	1.3	15.5		5	0.1
	1994-1995	1.3	15.5		5	0.07
	1996-1997	1.3	15.5		5	0.05*
	1998	1.3	15.5		4	0.05*
	2004	1.3	15.5	2.5		0.05*

Note: *.07 g/bhp-hr in-use

Table 8: U.S. Nonroad Compression Ignition (CI) Engine Emission Standards

Net Power kW(Hp)	HC g/kW-hr (g/bH p-hr)	CO g/kW-hr (g/bH p-hr)	NO_x g/kW-hr (g/bH p-hr)	PM g/kW-hr (g/bH p-hr)
$130 ($175)	1.3	11.4	9.2	0.54
	(1.0)	(8.5)	(6.9)	(0.4)
$75 to =130 ($100 to <175)	--	--	9.2	--
			(6.9)	
$37 to <75 ($50 to <100)	--	--	9.2	--
			(6.9)	
Net Power kW(Hp)	HC g/kW-hr (g/bH p-hr)	CO g/kW-hr (g/bH p-hr)	PM g/kW-hr (g/bH p-hr)	
$130	1.3[1]	5.0	0.54[1]	
($175)	(1.0)	(3.7)	(0.40)	
$75 to <130	1.3	5.0	0.70	
($100 to <175)	(1.0)	(3.7)	(0.52)	
$37 to <75)	1.3	6.5	0.85	
($50 to <100)	(1.0)	(4.8)	(0.63)	

Note:
[1] Consistent with the current California standards.

4.3 European Union

Table 9 and 10 outline the European Union (EU) standards for nonroad diesel engines.

Table 9: Stage I Standards

Net Power (P) (kW)	CO (P) (g/kWH)	HC (g/kWh)	NO$_x$ (g/kWh)	PM (g/kWh)
130#P<560	5	1.3	9.2	0.54
75#P<130	5	1.3	9.2	0.7
37#P<75	6.5	1.3	9.2	0.85

Table 10: Stage II Standards

Net Power (P) (kW)	CO (P) (g/kWH)	HC (g/kWh)	NO$_x$ (g/kWh)	PM (g/kWh)
130#P<560	3.5	1	6	0.2
75#P<130	5	1	6	0.3
37#P<75	5	1.3	7	0.4
18#P<37	5.5	1.5	8	0.8

The EU has had regulations governing on-road diesel engines as well. A summary of these and possible future requirements are shown in Table 11.

Table 11: Standards for Heavy-Duty Engines (g/kWh)
ECE 24.03 and EU Directive 72/306/EEC

	Class	Date	NO$_x$ (g/kWh)	HC (g/kWh)	CO (g/kWh)	PM (g/kWh)
EURO I (*)	# 85 >85	01.10.93 01.10.93	9.0 9.0	1.2 1.2	4.9 4.9	6.8 0.4
EURO II (*)		01.10.96	7.0	1.1	4.0	1.5
EURO III		>2000	5.04	6.6	2.09	0.1
EURO IV		>2005	2.56	4.1	2.76	0.8

Source: Reference 14

5.0 Diesel Exhaust Emission Control for the Underground Mining Industry

5.1 Catalyst Technology

Diesel exhaust emission control has been used in the underground mining industry for well over twenty years. In fact, some of the first applications for diesel oxidation catalysts were in the mining industry. These first catalysts were used primarily for the control of CO and aldehydes to address asphyxiation concerns as well as odour. As the health effects of diesel exhaust became better know, more attention to catalyst formulation became the norm. Catalysts were formulated to be more selective — that is, formulated in a manner to perform the desired reactions but to minimize undesired reactions, such as converting NO to NO_2. Attention was also focussed on the toxic emissions of catalysts and the mutagenic potential of the exhaust. Catalysts were formulated to reduce the toxic emissions and to leave the mutagenic potential of the exhaust, as measured by Ames testing, unchanged or decreased.

A report reviewing recent work carried out in a tunnelling operation in Switzerland summarized the use of oxidation catalyst for construction site diesel engines as follows:

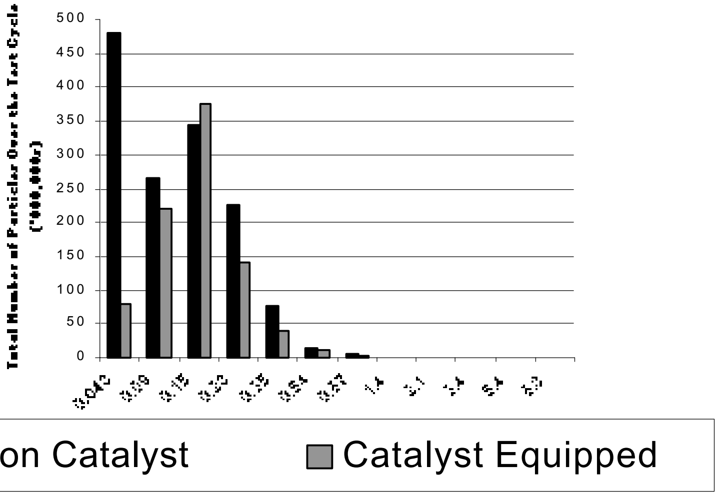
> “The oxidation catalyst does not reduce the combustion particulates (soot).
> The oxidation catalyst produces sulfate particulates.
> The oxidation catalyst has unfavorable gaseous phase reaction (increased toxicity).
> The positive effects of oxidation catalyst are irrelevant for construction site diesel engines.” (ref. 18).

The statements were made in reference to testing that was carried out in a tunnel under construction in Switzerland and therefore, has some relevance to underground mining applications.

The conclusion of the tunnel study are more negative with regard to catalyst technology than is justified. Catalyst technology has been, and probably will remain, a viable and effective option for the underground mining industry to reduce underground miners’ exposures to diesel emissions for a number of reasons.

Recent work at London Transport Buses (LTB) in England investigated the effects of using diesel oxidation catalysts over driving cycles derived from actual in-use operation in combination with low sulphur diesel fuel (0.05%) (ref. 19). An electrical low pressure impactor (ELPI) was used to determine the effect of the technology on ultrafine particles. The LTB testing showed that the catalyst fitted to two buses reduced HC emissions by more than 80 percent, CO emissions by over 90 percent, and PM emissions by more than 40 percent. Accompanying the total PM emission reduction were decreases not only in mass emissions at all size ranges measured, but also reductions in the number of particles emitted for all size ranges measured as indicated in Figures 11 and 12.

Figure 11: Particle Number Distribution



The effect of catalyst technology on ultrafine particles is a relatively new field, and the potential for the effect to be positive should not be dismissed as the above LTB testing would seem to indicate.

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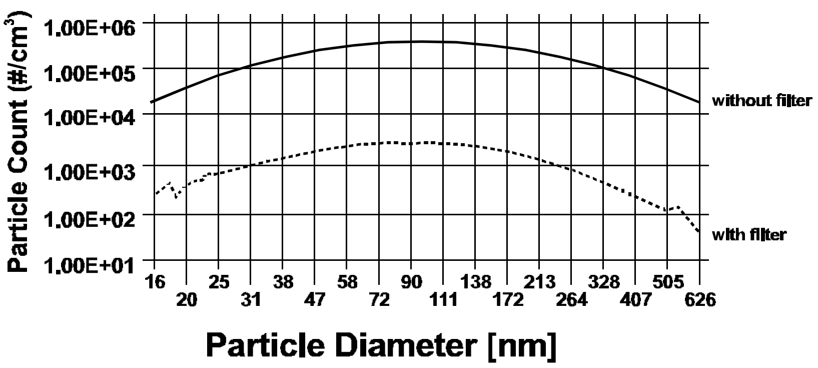
Regarding the negative impact on gaseous emissions (NO to NO_2), catalysts can be and have been formulated to minimize this reaction. In fact, the Western Australian Department of Mines requires catalyst manufacturers to submit data to the agency outlining "the efficiency of the

Figure 12: **Particle Number Distribution**



Source: Reference 21

product with hydrocarbon and carbon monoxide, and the ability to sufficiently suppress the unwanted oxidizing action on the oxides of nitrogen and sulphur" (ref. 20). Currently, two manufacturers have been approved, indicating the catalyst can be formulated to address these unwanted reactions if the NO to NO_2 shift is given as a design criteria. Furthermore, any increase in NO_2 emissions should be weighed against significant decreases in other toxic emissions including PAHs. The production of sulfate emissions can also be minimized in designing the catalyst formulation, but the use of very low sulphur diesel fuel remains another option and will also provide the catalyst designer more flexibility in targeting other pollutants more aggressively. Sulfate formation is also a function of exhaust gas temperature and many of the utility vehicles found in underground mines may have duty cycles for which sulfation is not an issue.

Furthermore, as development continues on lean NO_x emission control catalysts and commercialization occurs, catalyst technology may afford underground mine operations with a simple, effective means of simultaneously reducing CO, HC, NO_x, and PM emissions from diesel-powered vehicles.

5.2 Diesel Particulate Filters

Diesel particulate filters were first commercialized in underground mines in 1986 and have been successfully used in some areas (ref. 21) Although their use is not widespread, where properly applied, they have proven to be very effective at reducing diesel PM emissions and have proven durable with filters, lasting thousands of engine operating hours. DPFs have traditionally been used on underground production vehicles where exhaust gas temperatures often exceed 400EC allowing the catalytic coating to auto-ignite the collected PM (regeneration). Several advances, including: fuel-borne catalysts, catalysts placed in front of the filter, improved catalyst coatings, as well as more reliable burner technologies (active systems), have reduced the temperature required or in the case of active systems provided a reliable means to regenerate the filters and have made their potential use more widespread in underground mining applications.

Another advantage of DPFs, besides their ability to remove greater than 90 percent of the PM emissions from the exhaust of diesel engines is their effect on the utlrafine particles. In the afore mentioned VERT study, filter technology was found to have a dramatic effect on ultrafine particle emissions, as shown in Figure 13, where utra-fine particles were reduced by several orders of magnitude. Although different filter materials were investigated and results varied, all filters studied had the net effect of reducing fine and ultrafine particles.

5.3 Selective Catalytic Reduction

With the introduction of electronically-controlled engines in the underground mining industry, the possibility of employing SCR is now feasible to simultaneously control PM, HC, and NO_x emissions. In order to apply SCR technology, the urea injection system needs to be "mapped" to the specific engine the SCR unit is to be used in conjunction with. If this mapping has not already been performed, this work would have to be done up front. Most mapping for urea injection has been performed for diesel engines used in onroad vehicles; nonetheless, if the mining industry showed a true interest in SCR technology, it is likely that manufacturers would carry out the necessary mapping to tap this market. Ammonia slip becomes an important concern when employing SCR to underground mining vehicles. This can be addressed in two ways: 1) design the system for conservative NO_x reductions thereby minimizing the amount of reagent to ensure it is all consumed, or 2) add an oxidation catalyst to the system to oxidize any ammonia slip before it enters the working environment. The latter approach will allow for increased NO_x emission reductions and will more thoroughly account for any imprecision built into the injection algorithm.

SCR technology requires that urea be carried on board vehicles. This will require that the reagent be replenished as needed. This can be achieved by keeping a supply of reagent at fueling bays and topping up the on-board reservoir as needed. Reagent consumption typically equates to 2 to 3 percent fuel economy penalty.

5.4 Summary

Currently, only diesel oxidation catalysts and diesel particulate filters have been commercially supplied to the underground mining industry. Although newer technologies are emerging and are at different stages of development or commercialization, the most effective use of exhaust emission control technology available today to minimize underground miners' exposures to diesel particulate matter produced by underground mining vehicles would be a combination of diesel oxidation catalysts and diesel particulate filters. Wider spread use of filters is possible with the advances made in regeneration technology, and with proper application to mining vehicles, significant PM reductions can be achieved. Care must be taken to match a regeneration technology to the duty cycle of the vehicle. Where this is not feasible, diesel oxidation catalysts can be used to provide over a 25% reduction in PM emissions, accompanied by even greater reductions in CO and HC emissions while also eliminating the characteristic odor associated with diesel emissions.

The underground mining industry should also monitor the progress of the emerging technologies listed previously and as these become available incorporate them in to a strategy to most effectively reduce diesel emissions from underground mining vehicles.

Often a combination of technologies can be used not only to provide reductions in PM emissions but also CO and hydrocarbon emissions. An example of this would be to combine diesel oxidation catalysts with diesel particulate filters. Where NO_x emissions are a concern, lean-NO_x catalyst technology can be used in conjunction with a particulate control technology to provide simultaneous reductions of both pollutants as well CO and HC reductions. This approach, called four-way catalyst control, is being investigated to a larger extent recently as greater control of the four major diesel pollutants is being sought after.

Another area the mining industry could possibly exploit to enable further diesel emission reductions is underground diesel fuel quality. Limiting the sulfur content in fuel to under 10 ppm allows an exhaust emission control manufacturer to optimize its technology for the reduction of diesel emissions. More aggressive formulations can be used to maximize emission reductions, although care must be taken not to oxidize NO to NO_2 where this is potentially a concern.

Furthermore, the current sulfur levels in diesel fuel are actually a barrier to some diesel particulate filter technologies and all lean-NO_x technologies where the oxides of sulfur compete with the desired reactions or chemisorb onto the catalyst surface rendering the catalyst inactive until they are removed. Lower fuel sulfur levels, lower aromatics, and higher cetane also have a beneficial impact on engine-out emissions.

Several countries have already required the use of low sulphur diesel fuel for certain applications. These include Sweden, Finland, and the United Kingdom.

Engine technology can also provide the mining industry with a tool to reduce underground miners' exposures to diesel emissions. When purchasing new equipment, an operator can ensure that the cleanest available technology is purchased. When doing so, the operator should inquire whether the emissions performance is in any way compromised because of any changes to the engine's calibration which may be required for a given application. As a part of the U.S. EPA's recently passed nonroad heavy-duty diesel engine rulemaking, the Agency has provided engine manufacturers with optional low emitting certification standards -- referred to as Blue Sky engines. These optional standards provide manufacturers a mechanism by which to certify engines to lower emission standards. For many of the engines used in the mining industry, manufacturers can certify an engine to a PM emission standard from 0.09 g/bhp-hr to 0.16 g/bhp-hr depending on the rated horsepower. This is in the area already required for onroad engines (0.1 g/bhp-hr). Additional PM reductions could still be achieved by applying exhaust emission controls to those engines capable of meeting the optional standards without controls.

6.0 Cost of Exhaust Emission Control Technology

Table 12 indicates the approximate cost of commercially available exhaust emission control technology.

Table 12: Cost of Emission Control Technology

Technology	Cost ($US/hp)
Diesel Oxidation Catalysts	8 to 12
Diesel Particulate Filters	30 to 50
Selective Catalytic Reduction	~50

The cost of diesel particulate filters and SCR technologies can be considered high because of limited sales volumes. It is likely that these costs will decrease significantly if use of the technologies becomes more widespread. In fact, manufacturers of SCR systems for mobile sources are targeting a cost of approximately $US 2,500 for truck applications (ref. 13).

7.0 Conclusions

1) Diesel oxidation catalysts have been and will continue to be used effectively in underground mines to reduce emissions of CO, HC, and PM.

2) Properly formulated oxidation catalysts minimize the unwanted oxidation of NO to NO_2.

3) Diesel oxidation catalysts reduce toxic diesel emissions effectively.

4) Diesel particulate filters have been used effectively in certain applications to reduce >90% of PM emissions. Improvements in filter materials and new materials have enhanced the durability of these systems.

5) New regeneration technologies have increased the number of applications for which diesel particulate filter technology can be used.

6) Selective catalytic reduction is becoming commercially available for mobile sources.

7) Emerging technologies like lean-NO_x catalysts among others will probably play a role in reducing miners' exposures to diesel emissions in the years to come.

8) To reduce underground miners' exposure to diesel emissions, the mining industry can use strategies that include exhaust emission control technology, "clean" engine technology, and higher fuel quality.

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