

Emission Control of Diesel-Fueled Vehicles

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Manufacturers of Emission Controls Association
1660 L Street NW ❖ Suite 1100 ❖ Washington, DC 20036

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I. INTRODUCTION

Complaints about diesel smoke from trucks and buses have plagued city officials for years. More recently, health experts have expressed growing concerns about the health risks posed by the emissions from diesel powered vehicles. 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 size particle emitted by diesel powered vehicles. A study published in *The American Journal of Respiratory and Critical Care Medicine* confirmed the findings of the earlier work. Early this year, the National Resource Defense Council (NRDC) released a report titled, *BREATH TAKING: Premature Mortality Due to Particulate Air Pollution in 239 American Cities*. The report estimates that nationwide 64,000 people may prematurely die from heart and lung disease annually because of particulate air pollution. Diesel powered vehicles are also responsible for a significant percentage of the mobile source generated nitrogen oxide (NO_x) emissions that subsequently react in the atmosphere to form ground level ozone (smog) and contribute to acid rain. In an American Lung Association (ALA) report, *Breathless: Air Pollution and Hospital Admissions/Emergency Room Visits in 13 Cities*, the authors attribute 10,000 to 15,000 hospital admissions combined with 30,000 to 50,000 emergency room visits to elevated ozone levels during the 1993 or 1994 high ozone season.

Despite these problems, however, the diesel engine remains an attractive option for a world increasingly concerned with its environment and energy supply. First, most buses and heavy-duty trucks are powered by diesel engines for good reasons: 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 or to power city buses for up to 15-20 years.

Second, from a global-warming perspective, 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 and NO_x emissions, the diesel engine has very low emissions of hydrocarbons and carbon monoxide, both of which pose risks to public health and the environment.

Finally, engine and control system manufacturers from around the world have been engaged in programs to develop, optimize, demonstrate, and commercialize advances in engine designs and diesel emissions control devices such as trap oxidizers and catalysts for both OE and retrofit applications. As a result, the age of the clean, smokeless diesel appears to be at hand. In the U.S., several truck engine manufacturers equipped engines with diesel oxidation catalytic converters to meet the 1994 diesel particulate standard for light- and medium- duty trucks and over 1,500,000 converters have been installed on heavy-duty diesel vehicles since 1994. In

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Europe, well over 1,000,000 catalysts annually are being installed on diesel-powered automobiles. Catalysts are being installed on vehicles in other parts of the world as well.

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 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 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.

Several retrofit oxidation catalysts have been certified under EPA's urban bus retrofit/rebuild program which provide PM emission reductions of at least 25 percent for in-use urban buses. Recently, EPA announced its intention to approve the certification of an oxidation catalyst in combination with ceramic engine coatings and engine tuning to allow in-use buses to meet a 0.1 g/bhp-hr PM emission level under Option I of the program.

Technologies which combine catalyst or trap technologies with engine adjustments also are emerging for the control of both PM and NO_x emissions. One such technology has demonstrated over a 40 percent NO_x reduction while maintaining very low particulate emissions. The system uses ceramic engine coatings combined with fuel injection timing retard and an oxidation catalyst. Another example is a cerium based fuel additive trap system in combination with exhaust gas recirculation (EGR). This latter system has been shown to be capable of meeting a 2.5 g/bhp-hr combined NO_x and NMHC standard with PM emission less than 0.02 g/bhp-hr.

In addition, 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.

II. DIESEL EMISSIONS POSE HEALTH AND WELFARE CONCERNS

Diesel particulates are small (less than 2.5 microns) and complex substances. Particulate consists of an uncombusted carbon core, adsorbed hydrocarbons from engine oil and fuel, adsorbed sulfates, water, and inorganic materials such as those produced by internal engine abrasion.

Diesel particulates, because of their chemical composition and extremely small size, have raised a host of health and welfare issues. Health experts have expressed concern that they contribute to or aggravate chronic lung diseases such as asthma, bronchitis and emphysema, and there is growing evidence about the potential cancer

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risk from exposure to diesel particulate. These particles also impair visibility, soil buildings, contribute to structural damage through corrosion, and diesel exhaust gives off a pungent odor.

A comprehensive assessment of the available health information was carried out by the International Agency For Research on Cancer (IARC), in June 1988. The IARC Working Group concluded that diesel particulate is probably carcinogenic to humans. The term "carcinogen" is used by the IARC to denote an agent that is capable of increasing the incidence of malignant tumors.

In addition to the studies cited above, a 1993 EPA report, entitled *Motor Vehicle-Related Air Toxics Study*, listed diesel particulate as one of the most serious hazardous pollutants emitted from mobile sources. On June 17, 1994 the California Environmental Protection Agency released a preliminary draft report which concludes that sufficient evidence appears to exist to classify exhaust from diesel engines as a toxic air pollutant. Finally, recent health studies in Europe suggest that a primary health concern of particulate emissions is attributable to the carbon core. A bibliography of health effects studies on particulate is available from MECA.

NO_x emissions from diesel engines pose a number of health and environmental concerns. Once in the atmosphere, NO_x reacts with volatile organic compounds (VOC) in the presence of sunlight to form ozone. Ozone is corrosive and contributes to many pulmonary function problems. Ozone is particularly troublesome to children and the elderly. The ALA reported 10,000 to 15,000 hospital admissions combined 30,000 to 50,000 emergency room visits were made in the 1993 or 1994 high ozone season in 13 American cities because of elevated ozone levels. Ozone also can destroy vegetation, reduce crop yield, and damage exposed materials by contributing to cracking, fading, and weathering. NO_x emissions themselves can damage respiratory systems and lower resistance to respiratory infection. Like ozone, children and the elderly are particularly susceptible to NO_x emissions.

Diesel trucks and buses are a significant source of mobile source generated emissions. Uncontrolled diesel vehicles emit 30 to 70 times more particulate matter than gasoline vehicles equipped with catalytic converters. In the U.S., diesel trucks and buses are also responsible for a major portion of total mobile source generated NO_x and particulate emissions. For example in California, heavy-duty diesel trucks alone are responsible for approximately 34 percent of mobile source generated NO_x, as well as approximately 83 percent of mobile source generated particulate emissions. Diesel engines currently power the majority of large trucks and buses. The world production of diesel engines used in motor vehicle exceeds eight million units annually, with engines for medium- and heavy-duty trucks and buses making up approximately 45 percent. In Western Europe, diesel engines are used extensively on passenger cars and light trucks at a rate of approximately two million vehicles annually.

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Diesel emissions from buses and urban trucks are particularly troublesome because they frequently are emitted directly into the breathing zone where we work and recreate. A study performed in downtown Manhattan, showed the diesel engines were responsible for over 50 percent of total PM₁₀ emissions.

III. CONGRESS, THE U.S. EPA AND CALIFORNIA TAKE ACTION

The U.S. Congress recognized the health risks posed by diesel particulate, and significant contributions to the NO_x inventory by diesel-powered heavy duty engines. Consequently, as part of the 1977 Clean Air Act Amendments established specific, technology-forcing requirements for controlling these emissions. In the early 1980's EPA established particulate and NO_x standards for heavy-duty trucks and buses. The NO_x standards took effect in 1985 with the particulate standards taking effect in 1988. California subsequently adopted EPA's particulate standards for both light- and heavy-duty vehicles.

Congress tightened diesel emission standards further in the Clean Air Act Amendments of 1990. This legislation established a 0.1 g/BHP-hr particulate standard for 1993 model year buses, and made it even more stringent (between 0.05 and 0.07 g/BHP-hr) for 1994 and later urban bus engines. At the same time, the 1991 5.0 g/BHP-hr NO_x standard was tightened to 4.0 g/BHP-hr for 1998 and later model year engines. The Amendments also tightened the particulate standards for new light-duty vehicles and required EPA to establish emission standards for rebuilt urban bus engines beginning in 1995. EPA established the standards required by Congress and adopted emission standards for rebuilt 1993 and earlier model year urban bus engines. Rebuilt engines will be required to meet a 0.1 g/BHP-hr particulate standard if retrofit technology is available.

In June 1993, California adopted EPA's particulate standards for 1994 and later model year (LMY) urban buses. In July of 1995, EPA, CARB, and the Engine Manufacturers Association (EMA), announced a statement of principles (SOP) for new heavy-duty engine national standards. EPA has since published a Notice of Proposed Rulemaking and is currently finalizing the rule. The new requirements would take effect in 2004 and would require heavy-duty engines to meet a combined NO_x and NMHC standard of 2.5 g/bhp-hr and a particulate standard of 0.1 g/bhp-hr. As a part of the agreement, the signatories agreed to undertake research to investigate the possibility of heavy-duty engines reducing NO_x emissions to 1.0 g/bhp-hr and particulate emissions to 0.5 g/bhp-hr while maintaining engine performance, reliability, safety, durability, and efficiency. The progress of this effort will be reviewed in 1999.

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Table I

HEAVY DUTY TRUCKS (8,500 lbs GVWR* or over)		
	PM g/BHP-hr	NO_x g/BHP-hr
1988-1990	0.6	6.0
1991-1993	0.25	5.0
1994-1998	0.1	5.0
1998 and LMY	0.1	4.0
URBAN BUSES		
	PM g/BHP-hr	NO_x g/BHP-hr
1988-1990	0.6	6.0
1991-1992	0.25	5.0
1993	0.1	5.0
1994-1995	0.07	5.0
1996-1997	0.05**	5.0
1998 and LMY	0.05**	4.0
*Gross vehicle weight rating **0.07 standard in-use		

EPA, CARB, the Compression Ignition (CI) engine and equipment industry in September 1996 signed an SOP for nonroad heavy-duty engines. Earlier this year, EPA issued an ANPRM outlining stricter PM and NOx emission requirements for all sizes of nonroad diesel engines.

In late 1996 EPA proposed tightening the National Ambient Air Quality Standards (NAAQS) for PM_{2.5} while maintaining the current PM₁₀ NAAQS. The Agency has proposed a new annual PM_{2.5} standard of 15µg/m³ and new 24-hour PM_{2.5} standard of 50µg/m³.

Solving the Diesel Emission Problem

With the prospect of tighter tailpipe and air quality standards in place, vehicle and engine manufacturers, control device manufacturers, independent technical and fuel experts, university researchers, and others around the world turned their energy and considerable resources to developing ways to reduce diesel emissions. The progress made to date has been dramatic.

Engine manufacturers have developed or are developing a series of engine modifications which have and will significantly reduce emissions, including: 1) fuel injection; 2) electronic engine controls; 3) combustion chamber modifications; 4) air handling improvements; and 5) reduced oil consumption.

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In order to achieve very low levels of particulate emissions, manufacturers also have turned to the development of exhaust control devices, that is, devices added to clean up the exhaust after it leaves the engine. Several types of devices are available.

First, a flow-through oxidation catalytic converter installed on a vehicle to operate on currently available low sulfur fuel can reduce the soluble organic fraction of the particulate by as much as approximately 50 percent and total particulate by as much as approximately 30 to 40 percent. Smoke emissions from older vehicles can be reduced by over 50 percent and a catalyst can virtually eliminate the obnoxious odor of diesel exhaust.

First generation trap systems relied external heat sources to regenerate, or clean the collected particulate from the trapping medium. In some markets like forklift trucks, simplified higher energy systems have been found to be useful and are sold commercially in Europe. Research and development has resulted in second generation trap systems of far less complexity. These systems rely fuel additives like cerium, copper, and platinum, catalysts placed in front of the filter, or catalysts coated directly on the filter to initiate the regeneration process as well as simplified burner systems.

Second, diesel particulate trap oxidizers or diesel particulate filters can achieve up to, and in some cases greater than, a 90 percent reduction in particulate. The trap is extremely effective in controlling the carbon core of the particulate, which recently has attracted the attention of health experts as posing a possible serious health threat.

Both the oxidation catalyst and trap oxidizer have been shown to generally decrease the levels of polyaromatic hydrocarbons, nitro-polyaromatic hydrocarbons and mutagenic activity. In some applications, catalyst and trap technologies can be combined to provide even greater control and can be used in combination with engine management techniques, e.g. injection timing retard and exhaust gas recirculation (EGR), to provide significant control of both particulate and NO_x.

IV. FLOW-THROUGH OXIDATION CATALYSTS OFFER AN EFFECTIVE CONTROL STRATEGY

The diesel oxidation catalyst has become a leading control strategy in the U.S. and elsewhere to help address the particulate problem. In the U.S., interest in oxidation catalyst technology stems from two developments. First, through engine modifications, a significant portion of heavy-duty truck engine models have engine-out particulate emission levels near the 0.1 g/BHP-hr standard. For those engines, using oxidation catalysts to control the soluble organic fraction (SOF) of the particulate can provide the additional particulate control needed to comply with the standard. Second, EPA since 1993 has required low-sulfur fuel (0.05% sulfur by

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weight) for highway diesel-powered vehicles. This has facilitated the application of catalyst technology to diesel-powered vehicles. The very low fuel sulfur levels (< 50 ppm) available in several European countries enhances catalyst technology even further.

Operating Characteristics

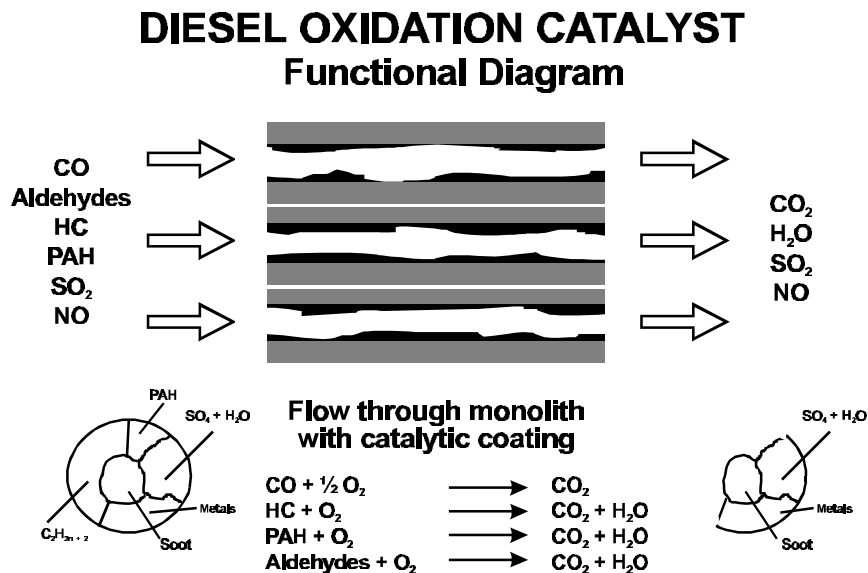
Using a flow-through oxidation converter on diesel-powered vehicles is not a new concept. Oxidation converters have been installed on off-highway vehicles around the world for over 20 years.

The idea 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 (HC) 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 1.

Figure 1

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)

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Technical Paper (SAE No. 900600) 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. Destruction of the SOF is important since 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 smoke emissions on older vehicles. A recent SAE paper (940235) reported that 120 buses in Argentina retrofitted with oxidation catalysts averaged over a 50% reduction in smoke opacity levels during a field demonstration.

Combining an oxidation catalyst with engine management techniques can be used to reduce NO_x emissions from diesel engines. This is achieved by adjusting the engine for low NO_x emissions which is typically accompanied by increased CO, HC, and particulate emissions. An oxidation catalyst can be added to offset these increases, thereby rendering the exhaust low in all of the pollutants. Often, the increases in CO, HC, and particulate can be reduced to levels lower than otherwise could be achieved. In fact, a system which uses an oxidation catalyst combined with proprietary ceramic engine coatings and injection timing retard to provide over a 40 percent NO_x reduction while maintaining low particulate emissions has been approved under EPA's urban bus rebuild/retrofit program.

The sulfur content of diesel fuel is critical to applying catalyst technology. Catalysts used to oxidize the SOF of the particulate can also oxidize sulfur dioxide to form sulfates, which is counted as part of the particulate. Catalyst formulations have been developed which selectively oxidize the SOF while minimizing oxidation of the sulfur dioxide. However, the lower the sulfur content in the fuel, the greater the opportunity to maximize the effectiveness of oxidation catalyst technology. As noted above, the low sulfur fuel (0.05%) which was introduced in 1993 throughout the U.S. has facilitated the application of catalyst technology to diesel-powered vehicles. As previously mentioned, the very low fuel sulfur content (< 0.005%) available in several European countries has further enhanced catalyst performance. These very low levels of fuel sulfur also allowed the early introduction of a particulate trap system which uses a catalyst placed in front of the filter to initiate regeneration. The system is currently being optimized for use with higher sulfur U.S. fuel.

Furthermore with EGR being a likely candidate technology to meet the lower proposed standards as outlined above, minimizing the fuel sulfur content of diesel fuel will minimize the adverse corrosive effect that SO₂ laden exhaust gases could otherwise have on engine components and insure durable low emission engines will exist.

Operating Experience

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The use of diesel oxidation catalyst technology is increasing. Over 250,000 diesel powered off-road engines worldwide have been equipped with catalysts. Catalysts have been used on forklift trucks and underground mining and construction vehicles among other types of vehicles. Since 1994, over 1,500,000 oxidation catalysts have equipped on light- and medium heavy-duty trucks in the U.S. Oxidation catalysts have been used on bus engines to meet the urban bus engine 1994 0.07 g/bhp-hr and 1996 0.05 g/bhp-hr. Today, virtually all new urban buses being factory equipped with oxidation catalysts. Finally, Mercedes Benz has introduced the 1995 E 300 diesel sedan equipped with a diesel oxidation catalyst which meets the stringent California 0.08 gpm particulate standard. In Europe, over 1,000,000 diesel automobiles annually are being equipped with catalysts. Operating experience with oxidation catalysts on a variety of different vehicles can now be considered mature and the experience has proven the technology to be reliable both from an emissions point of view as well as durability point of view.

A growing number of companies are involved in developing and applying catalyst technology to diesel engines. These companies include Corning Incorporated, Degussa Corp., Engelhard, Engine Control Systems, Ltd., Johnson Matthey/Emissionsteknik, International Catalyst Technology, Inc., NGK-Locke, Walker Manufacturing, Inc. and others.

Catalyst Retrofit Opportunities

Oxidation catalysts can play a significant role in removing particulate and smoke from existing diesel engines and as noted above can be used in combination with engine management techniques to control NO_x emissions. Retrofitting oxidation catalysts on existing diesel engines is relatively straight-forward. For example, in many applications the oxidation catalyst can be retrofitted as a muffler replacement. Indeed, many of the catalysts used on off-road engines are retrofits and recently, approximately 7,500 oxidation catalysts have been retrofitted to urban buses in the U.S. In Europe, close to 1,000 catalytic oxidizers have been equipped to in-use trucks and buses since 1995.

For optimum results, the existing engine should be rebuilt to manufacturer's specifications before the catalyst is retrofitted on the engine. Care also must be taken to properly match the catalyst to the specific engine applications. Diesel fuel with low sulfur (0.1% weight or less) is recommended. Finally, engines equipped with catalysts should receive routine maintenance. With particularly dirty engines, periodic removal and cleaning of the catalyst should be considered. However, catalysts employing larger cells, e.g. 200 cells per inch (cpi), can considerably minimize the risk of plugging and fouling.

Oxidation catalysts have also been retrofitted throughout the world for particulate control. In Chile, over 1000 urban bus engines have been retrofitted with

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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. Delivery trucks in Mexico have also been retrofitted with catalysts

Hong Kong has recently embarked on a retrofit program for urban buses where the criteria used is a 25 percent smoke reduction.

Four catalyst-based systems have been approved by the U.S. EPA under the urban bus rebuild/retrofit program. Three of the approvals are for oxidation catalysts which provide more than a 25 percent reduction in particulate emissions as compared to the rebuild engine level. The fourth system not only provides particulate reductions, but also provides over a 40 percent reduction in NO_x emissions. This is accomplished by employing proprietary ceramic engine coatings in combination with retarding engine timing and an oxidation catalyst. The EPA has proposed approval of a fifth catalyst-based system which also uses ceramic engine coatings and would trigger the 0.1 g/bhp-hr PM emission requirement under Option I of the program. Also, as a growing number of states, led by California and Colorado, are implementing in-use heavy duty vehicle smoke checks with accompanying heavy fines for violations, catalyst retrofits may become an attractive strategy for helping to insure that older heavy-duty vehicles maintain opacity levels well below required limits.

V. DIESEL PARTICULATE TRAP OXIDIZERS OFFER A TECHNOLOGICAL SOLUTION TO CONTROLLING DIESEL PARTICULATE MATTER

Diesel particulate filters have been known to provide substantial PM emissions reductions for well over 10 years. As a result of the early work with filter systems, a number of second generation systems have been developed which have taken the complexity out of regeneration systems and provided for increased reliability and durability. These systems are currently being used and/or demonstrated in different countries throughout the world. A few of the countries of note include:

- Sweden where over 2,000 second generation systems are in-use with some having surpassed 250,000 miles of use,
- Korea with over 200 systems being demonstrated and 1,475 systems commercially being used on trucks and buses,
- Mexico with systems being tested for high altitude operation, and
- Switzerland with systems being tested for nonroad tunneling operations.

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Particulate filter systems have also been sold commercially in mining, construction, and materials handling industries for over 10 years.

Operating Characteristics

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 disposing of this trapped particulate 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.

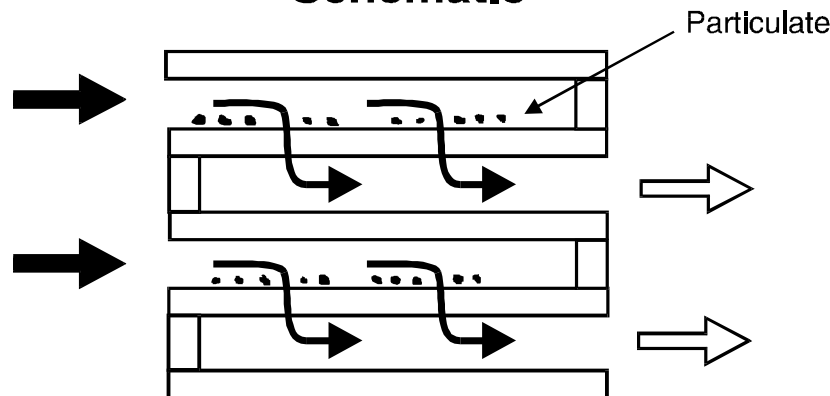
A complete trap oxidizer system consists of the filter and the means to facilitate the regeneration.

Filter Material A number of filter materials have been tested, including ceramic monoliths and woven fibers, woven silica fiber coils, ceramic foam, wire mesh, and sintered metal substrates. Collection efficiencies of these filters range from 50 percent to over 90 percent. Currently, the ceramic monoliths and woven fibers have been used commercially.

All of the 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, for example, 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 2 on page 12 shows an example of one filtration mechanism.

Figure 2

DIESEL TRAP OXIDIZER Schematic



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.

A recent SAE Paper (No. 940235) reported impressive results with an improved cordierite ceramic monolith filter. 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 trap. A number of techniques are available to bring about regeneration of traps. It is not uncommon for some of these various techniques to be used in combination. Some of these methods include:

- Using a catalyst-coated trap. The application of a base or precious metal coating applied to the surface of the filter reduces the ignition temperature necessary for oxidation of the particulate;
- Using a catalyst to oxidize NO to NO₂ which adsorbs on the collected particulate substantially reducing the temperature required to regenerate the filter.

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- Using fuel additives to reduce the temperature required for ignition of the accumulated material;
- Throttling the air intake to one or more of the cylinders, thereby increasing the hydrocarbon and carbon monoxide concentration in the exhaust as well as increasing the temperature;
- Using fuel burners, electrical heaters, or 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 particulate from the filter into a collection bag which is periodically discarded or burned; and
- Throttling the exhaust gas downstream of the trap. 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.

Some trap systems, to protect the filter from overheating and possibly being damaged, incorporate a by-pass for exhaust gases which is triggered and used only when exhaust temperatures reach critical levels in order to slow the regeneration process. The period during which the by-pass is operated is very short and relatively infrequent. Some systems are also designed with dual filters in which one filter collects while the other is being regenerated.

Trap Oxidizer System Evolution

First generation trap oxidizer systems, which were installed on a number of buses in the U.S. in the early 1990s, used electric heaters as the principle means of regeneration. These systems generally performed well when the trap system was maintained according to the manufacturer's specifications. However, failures have occurred when maintenance was not performed. Also, these systems proved quite complex and expensive. Recently, EPA allowed engine manufacturers to remove traps on 1990-1993 bus engines and to replace them in some cases with diesel oxidation catalysts.

Learning from the experience gained from these first generation systems, trap oxidizer manufacturers focussed on systems which are 1) less complex and less costly, 2) use passive or near passive regeneration, 3) are more flexible, and 4) are targeted for specific applications.

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Using *improved catalyst coatings* to facilitate regeneration remains an attractive option, particularly for four-stroke engine applications where exhaust temperatures are typically higher than with two stroke engines. A trap system with an appropriate catalytic coating can combine the best features of both types of control technologies giving both particulate and gaseous emissions control. One trap manufacturer has combined using a catalyst with a small auxiliary electric heater. Another uses a combination of a catalyst in front of a filter to convert NO to NO₂ to significantly reduce the temperature required for regeneration. Both types of systems have been commercialized and have achieved excellent results in field demonstrations. Systems using improved catalysts coatings applied directly on to the filter media are in-use in both road and nonroad applications.

Using *fuel additives* to reduce the temperature required for ignition of the accumulated material has recently received considerable attention and is achieving impressive results. Metal-containing (e.g. Cerium, Copper, Iron, Platinum) fuel additives are used to enhance the oxidation process under normal vehicle operating conditions. The system is very simple; it consists of the filter and the diesel fuel additive. This approach is being successfully demonstrated worldwide. The resultant metal oxides become embedded in the core carbon particulates during the combustion process. As such they are in intimate contact with the carbon core. The metal oxides serve as effective catalytic surfaces for the combustion of the solid particulate matter. This occurs at reduced temperatures relative to temperature required for ignition in the absence of fuel additives. It is this principal of operation that eliminates the need, for the most part, of costly and complex control hardware. The additives are formulated to ensure that neither fuel quality nor the resulting combustion process are adversely affected and in fact, in some instances, may be improved.

Some examples of individual company efforts to develop "next generation" trap systems include:

Catalyst Based Technologies

- Engelhard has developed several different catalytic soot filter (CSF) versions. Their patented Pt-based coatings impregnated into the porous filter wall surfaces act in three ways to eliminate diesel emissions. First, the catalytic surfaces oxidize gaseous HCs and CO as in a normal oxidation catalyst; second, the SOF collected on the CSF surfaces are destroyed as in an oxidation catalyst; and third, the trapped carbonaceous soot is ignited in direct physical contact with the catalyst particles. Carbonaceous soot will auto ignite in excess air at approximately 550 to 600°C. Incorporation of precious metal onto the CSF enables the ignition of the collected soot to occur at temperatures as low as 375°C (even lower with very low sulfur fuel).

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The CSF has been used for many years on mining equipment where high duty loads create exhaust gas temperatures above 450°C - regeneration of the CSF occurs spontaneously without the need for a burner or heater. More recently, the CSF was applied to eleven Orange County Transit Authority (OCTA) buses equipped with 4-stroke Cummins L-10 engines and operated with < 0.05% S diesel fuel. The first bus, in random route service in the OCTA system, was in service for over 3.5 years and accumulated over 211,000 miles. Some of the other buses that had been retrofitted and operated in excess of 100,000 miles. Regeneration of the collected soot occurred spontaneously without any problems. The program came to a successful completion.

Engelhard also markets a trap oxidizer systems which incorporates a catalyzed filter and an electric burner for industrial applications like forklift trucks. The filter medium of the systems can either be a ceramic wallflow filter or ceramic woven fibers. The filter collects particulate emissions until it needs to be regenerated. The operator simply drives to a regeneration station and plugs the system into the station which both supplies 220 volts for the burners and combustion air for controlled regeneration.

- Engine Control Systems Ltd. has been supplying a catalyzed trap system to the off-road market since 1986. The traps have been found to have a useful life about equivalent to the number of operating hours required for engine rebuild or replacement.
- Johnson Matthey's filter system for reducing particulate emissions from diesel engines has two stages: an oxidation catalyst and a particulate filter. The catalyst is used to oxidize NO to NO₂ which is subsequently used to enhance oxidation of the collected particulate trapped downstream in the filter. The catalytically formed NO₂ is adsorbed onto the trapped particulate thereby substantially reducing the temperature required for combustion. The system relies solely on the conversion of NO to NO₂ by the catalyst. Three key requirements for the system to perform properly are a reasonable balance between NO_x and particulate emissions, a duty cycle which regularly gives rise to exhaust gas temperatures in excess of 260°C, and the use of low sulphur fuel.

In addition to extensive testing done at Johnson Matthey's diesel technical center in Sweden, testing has begun in the U.S. Results have shown particulate emissions levels in the 0.01 to 0.03 g/bhp-hr range. Over 2,000 systems have been retrofitted to urban buses as a part of the country's Clean Cities Program with some of the systems having surpassed the 250,000 mile mark. The work in the U.S. also includes

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optimizing the systems to fuels containing higher sulfur levels. Systems have also been retrofitted to vehicles in the U.K. including buses, delivery trucks and refuse collection trucks. Germany, Holland, and Belgium have also expressed an interest in demonstrating the technology.

Additive Based Technology

- 3M Company has developed two filter systems which use woven ceramic fibers as the filter media. One system employs an Iron-based fuel additive to induce regeneration while the other employs electrical heater wires within the cartridges themselves.

3M has over 750 systems in-use in both on-road and non-road applications throughout the world for over 3 years. Some of the off-road systems have operated for over 10,000 hours with some of the on-road systems having accumulated in excess of 150,000 km.

- Clean Diesel Technologies has developed a platinum-based fuel additive for use in conjunction with diesel particulate filter systems. The additive is mixed with the fuel in extremely low concentrations, 0.15 to 0.25 ppm, to assist in regeneration of a loaded diesel particulate filter and provide additional gaseous emissions reductions. Testing on a Cummins L-10 engine has shown that system provides significant reductions in CO, HC, and PM can be achieved using the platinum-based fuel additive in combination with a diesel particulate filter.
- Engine Control Systems Ltd. has been demonstrating and developing a particulate filter system which uses a copper-based fuel additive for regeneration and have applied for certification under U.S.-EPA's urban bus rebuild/retrofit program. Certification data has shown filtration efficiencies in excess of 95 percent. In fact a 1985 Cummins L-10 engine that produced 0.46 g/BHP-hr was tested at particulate levels as low as 0.02 g/bhp-hr, a 95.6 percent reduction. The testing was performed over the HDD-FTP and represents a composite between both the hot and cold cycles.

The system uses small quantities (~ 50 ppm) of additive to lower the temperature required for regeneration of the filter to levels suitable for urban bus applications including both two and four stroke engines. Furthermore, the filter itself is the only hardware required for centrally-fueled vehicles.

Emission Control of Diesel-Fueled Vehicles

- Rhône-Poulenc, in partnership with other companies, is developing a technology to substantially reduce both particulate and NO_x emissions from heavy-duty diesel engines. The system consists of a cerium-based fuel additive which is used in conjunction with a particulate trap. The cerium promotes highly efficient combustion of the trapped particulates, so the particulate emissions are reduced by 90 percent. Rhône Poulenc is the manufacturer of the cerium fuel additive. The system is being evaluated worldwide in both retrofit and original equipment applications.

The system has been retrofitted to eight buses in Korea which have accumulated over 30,000 km. In Europe, the systems has been equipped to two, 2 liter delivery vans which have accumulated in excess of 30,000 miles. In order to determine the performance of the system at high altitude, Rhône Poulenc has initiated a retrofit program in Mexico City. It has already been determined that adding the additive to the fuel is in itself beneficial. Running additized fuel without a filter has reduced particulate emissions by 15 percent to 20 percent. This work is being enhanced with a laboratory evaluation at SWRI.

Rhône Poulenc has also carried development work using the additive, a filter, and EGR on a U.S. medium heavy-duty engine designed to meet post 1998 emission requirements. The system, still undergoing optimization, has reduced emissions to a 0.02 g/bhp-hr PM emission level as well as a 2.16 g/bhp-hr NO_x level. Rhône Poulenc is also participating in preliminary development work to evaluate the retrofit potential for this system.

Trap Oxidizer Impacts on Engine and Vehicle Performance

Optimizing a trap oxidizer system to a particular application has as a prime engineering goal the elimination (or minimization) of any adverse effects of the system on engine or vehicle performance. Evaluations with trap oxidizer development suggests these goals are attainable. Several specific effects are discussed below:

Nitrogen Oxides, Hydrocarbon, and Carbon Monoxide Emissions Non-catalyzed trap systems appear to have little or no effect on NO_x or CO emissions. Experience with the catalyzed trap system indicates that HC and CO emissions have been reduced to a considerable degree (in the range of 60-90 percent) with no adverse impact on NO_x emissions. By the use of EGR and other approaches that rely on the NO_x-particulate matter tradeoff, to control NO_x emission levels the use of trap technology increases in its attractiveness.

Emission Control of Diesel-Fueled Vehicles

Unregulated Pollutants Though difficult to quantify, one manufacturer has found that ceramic traps significantly reduce gas phase aromatics and noise. The experience with catalyzed traps indicates that there is a virtually complete reduction in odor 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 are modifying catalyst formulations to reduce any sulfates emitted to an acceptable level. The low sulfur fuel (0.05% by weight) currently available in the U.S. has greatly facilitated these efforts.

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

Fuel Economy A very slight fuel economy penalty has been experienced with trap oxidizer 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 the Athens program, described on the next page, no noticeable fuel penalty was recorded when the trap was regenerated with a cerium fuel additive (SAE 920363).

Engine Wear and Vehicle Maintenance 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.

Vehicle Acceleration and Driveability Various trap systems have been designed so that driveability should not be affected, or at least effects can be minimized, most notably by limiting back pressure.

Safety Safety is a paramount consideration in developing a trap system. In establishing the particulate standards, EPA expressed its belief that safe systems can be developed. Trap system manufacturers likewise are confident that safe systems can be and have been developed.

VI. ADVANCES IN LEAN-NO_x CATALYST TECHNOLOGY

Conventional NO_x reduction catalyst technology used on gasoline engines cannot be applied to diesel engines because of the excess oxygen in the exhaust. Research is underway to develop catalyst technology that can reduce NO_x in an oxygen-rich exhaust -- this technology has been dubbed the diesel lean NO_x catalyst. While the technology is in the early stages of development, the progress being made is very encouraging.

Emission Control of Diesel-Fueled Vehicles

Diesel lean NO_x catalyst developments have focused on formulations using zeolites. Zeolites are characterized as small molecular cages - that is, molecules formed in such a way that the interior is an open structure with defined micropores or "tunnels" leading to this interior opening. It has been found that when, for instance, copper is incorporated onto certain zeolites, that NO_x can be reduced even though the surrounding atmosphere is oxidizing if certain hydrocarbons are present.

The HCs must be able to penetrate the tunnels leading to the interior opening where it is believed they enter into the process of oxidation and in doing so decrease the oxygen present so that the local environment is net rich. Therefore, the reduction of NO_x can proceed. To insure an adequate supply of HCs is available to serve as reducing agents, strategies are being evaluated for utilizing on-board diesel fuel.

Another lean NO_x catalyst design uses precious metals in combination with zeolites. The mechanism thought to be dominant for such catalysts is as follows: NO_x is known to reduce on precious metal catalyst surfaces for one cycle - thereby leaving an oxygen rich surface. The HC is then thought to blanket a large area of precious metal oxygen rich sites and removes the surface oxygen to form CO₂, CO and H₂O and frees the precious metal surface for another NO_x reduction cycle. The engineering challenge with this lean NO_x catalyst strategy is to completely reduce NO_x to nitrogen.

In laboratory testing, diesel lean NO_x catalysts have achieved up to an 85% NO_x reduction. Vehicle testing with an advanced design catalyst achieved a 23% NO_x reduction coupled with a 50% decrease in CO and a 50% reduction in total particulate.

Although not yet commercial, lean-NO_x catalyst technology continues to improve and will likely become an available option for diesel emissions control in the not too distant future. Several recent SAE papers (SAE 950746 through SAE 950751, SAE 952495, and SAE 961129) report significant advances in durability, increased operating windows, and NO_x reductions.

In Germany, a limited number of selective catalytic reduction (SCR) systems have been tested on diesel trucks to substantially reduce NO_x emissions. This demonstration is going to be expanded to include an additional 500 systems.

Recently, Engelhard Corp., Clean Diesel Technologies, and Nalco Fuel Tech cooperated in demonstrating up to a 90% NO_x reduction using a urea-based SCR system on a 230 hp engine test. While the initial target is for stationary diesel engine applications, the technology will also be evaluated for mobile source applications.

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VII. CONCLUSIONS

- Diesel emissions from trucks and buses have raised health and welfare concerns, but a number of promising control strategies exist or are being developed that can greatly reduce emissions from diesel-powered motor vehicles.
- Alternative fuels such as methanol, natural gas and propane will play an important role in the future in fueling our transportation system and addressing the diesel particulate problem, but diesel fuel also will continue to be a major source of fuel because diesel engines are reliable, durable, energy efficient, and cost effective.
- Engine modification developments have helped reduce engine out particulate emissions.
- Oxidation catalyst technology can substantially reduce particulate, smoke and odor from diesel engines, and improvements in oxidation catalyst technology continue to evolve to further enhance the application of this technology to diesel engines.
- Trap oxidizer technology can reduce harmful particulate emissions by up to 90 percent or more, as well as substantially reduce smoke.
- Both oxidation catalysts and trap oxidizers can be use in conjunction with engine management techniques, e.g. injection timing retard or EGR, to reduce diesel particulate and NO_x emissions.
- Four oxidation catalysts systems have been approved under U.S. EPA's urban bus rebuild/retrofit program and another is pending.
- Second generation trap systems have been developed and are being demonstrated worldwide. Some of these systems have already been commercialized and have accumulated significant mileage in use.
- To meet the 0.1 g/BHP-hr particulate standard for trucks, flow-through catalytic converters has been a key control strategy.
- To meet the 0.07 g/BHP-hr and 0.05 g/BHP-hr particulate standards for buses, catalysts have been used.

Emission Control of Diesel-Fueled Vehicles

- Both trap oxidizers and oxidation catalysts will be available control options to help meet a 0.1 or lower g/bhp-hr PM standard in conjunction with a 2.5 g/bhp-hr combined NO_x and NMHC standard.
- As standards for off-road engines and vehicles are tightened in the future, both catalysts and traps will be available to provide significant reductions.
- Existing heavy-duty diesel-powered vehicles, particularly those operated in urban areas, pose a special problem to the air quality. Retrofit application of diesel oxidation catalysts and diesel particulate traps for both trucks and buses offers an opportunity to greatly reduce a significant source of particulate emissions.
- Advances continue in the development of lean-NO_x catalysts. Increased durability, broader operating windows, and higher NO_x reductions have all been achieved. It is expected that lean-NO_x catalysts in the future will be commercially available.
- SCR systems for NO_x control are being demonstrated in Germany with good success.