Emission Control Technology
for Stationary
Internal Combustion Engines

Status Report

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July 1997

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I. INTRODUCTION

Internal combustion (IC) engines are used in a variety of stationary applications ranging from power generation to inert gas production. Both spark ignition and compression ignition engines can be found. Depending on the application, stationary IC engines range in size from relatively small (~50 hp) for agricultural irrigation purposes to thousands of horsepower for power generation. Often when used for power generation, several large engines will be used in parallel to meet the load requirements. A variety of fuels can be used for IC engines including diesel and gasoline among others. The actual fuel used depends on the owners/operators preference but can be application dependent as well.

The operation of IC engines results in the emission of hydrocarbons (NMHC or VOC), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM). The actual concentration of these criteria pollutants varies from engine to engine, mode of operation, and is strongly related to the type of fuel used.

Various emission control technologies exist for IC engines which can afford substantial reductions in all four criteria pollutants listed above. However depending on whether the engine is being run rich, lean, or stoichiometrically and the emission control technology used, the targeted emissions vary as do the levels of control. For example, an oxidation catalyst can be used to control NMHC, CO, and PM emissions from diesel engines which inherently operate in a lean environment, whereas selective catalytic reduction (SCR) could be used to additionally control NOx emissions. More recently, lean-NOx catalysts have been demonstrated to provide greater than a 80 percent reduction in NOx emissions from a stationary diesel engine, while providing significant CO, NMHC, and PM control as well.

PM emissions from stationary diesel engines are more of a concern than those for IC engines using other fuels. Several emission control technologies exist for diesel engine PM control. Oxidation or lean-NOx catalyst can be used to not only reduce the gaseous emissions associated with the use of diesel engines but further provide significant PM control. Likewise, diesel particulate filter systems can be used to achieve up to and greater than 90 percent PM control while in some instances, also providing reductions in the gaseous emissions.

Additionally, special ceramic coatings applied to the combustion zone surfaces of the piston crown, valve faces, and head have shown the ability to significantly reduce NOx and PM emissions in diesel engines. These ceramic coatings can be used by themselves or combined with an oxidation catalyst to give even greater reduction of PM. Ceramic engine coatings change the combustion characteristics such that less dry, carbon soot, is produced. Also, when combined with an oxidation catalyst, ceramic coatings allow retarding of the engine to reduce NOx, while CO and particulates are maintained at low levels.

In the case of gaseous fuels, ceramic coatings have shown the ability to allow the user to operate their engines with timing significantly advanced generating higher power levels. Also, wider ranges of fuel composition and ambient air temperature fluctuations are tolerated without the deleterious effects of precombustion. Tests are currently underway to evaluate the effects of the coatings on specific emissions from gaseous fueled engines.

Emission control technology for stationary IC engines is currently available and can be used to provide substantial reductions in the CO, NMHC, NOx, and PM emissions from these sources in a cost-effective manner.

II. STATIONARY INTERNAL COMBUSTION ENGINES

Stationary applications for IC engines include:

- gas compression,
- pumping,
- power generation,
- cogeneration,
- irrigation,
- and inert gas production.

IC engines use a variety of fuels and run rich, lean, or stoichiometrically as outlined in Table 1. The engines used in these applications range in size from fifty horsepower to thousands of horsepower. There are cogeneration facilities in the U.S. which use several large engines in parallel to generate electricity.

Table 1: Engine Types and Fuels

Rich Burn	Natural Gas Propane Gasoline
Stoichiometric	Natural Gas Propane Gasoline
Lean Burn	Diesel Natural Gas Dual Fuel

Typical gaseous emission levels of some of these engines is included in Table 2.

Table 2: IC Engine Typical Emission Levels

Engine Type	Lambda*(ë)	Mode	Emission (g/bhp-hr)			
			NMHC	**CO**	**NOx**	**PM**
Natural Gas	0.98	Rich	0.3	13.9	8.3	Low
	0.99	Rich	0.2	8.0	11.0	Low
	1.06	Lean	1.0	1.0	18.0	Low
	1.74	Lean	1.0	3.0	0.7	Low
Diesel	1.6-3.2	Lean	0.3	1.0	11.6	0.25-0.8
Dual Fuel	1.6-1.9	Lean	0.5	2.5	4.1	NA

* ë is the ratio of the actual air to fuel ratio to the stoichiometric air to fuel ratio.

It is important to note that emissions vary from engine to engine and model to model. Nonetheless, the above values are representative of what may be expected. Natural gas, propane, and dual fuel engines are characterized by relatively low PM emissions, whereas diesel engines have relatively high PM emissions.

The difference between rich, lean, and stoichiometric engine operation lies in the air to fuel ratio. Stoichiometric engine operation is defined as having the chemically correct amount of air in the combustion chamber during combustion. Hence, perfect combustion would result in the production of carbon dioxide (CO_2) and water. However, perfect combustion not being possible results in the production of NMHC, CO, NOx, PM, and water as well. A rich-burn engine is characterized by excess fuel in the combustion chamber during combustion. A lean-burn engine, on the other hand, is characterized by excess air in the combustion chamber during combustion which results in an oxygen rich exhaust. Diesel engines inherently operate lean, whereas IC engines which use natural gas, gasoline, or propane can be operated in all three modes of operation.

III. GASEOUS EMISSION CONTROL OF STATIONARY IC ENGINES

Catalyst Control Technologies

The principle behind a catalyst for control of the gaseous emissions of a stationary IC engine is that the catalyst causes chemical reactions without being changed or consumed. An emission control catalyst system consists of a steel housing, whose size is dependent on the size of the engine for which it is being used, that contains a metal or ceramic structure which acts as a catalyst support or substrate. There are no moving parts, just acres of interior surfaces on the substrate coated with either base or precious catalytic metals such as platinum (Pt), rhodium (Rh), palladium (Pd), and vanadium (V) depending on targeted pollutants. Catalysts transform pollutants into harmless gases by causing chemical reactions in the exhaust stream. These reactions differ depending on the technology being used which further depends on whether the engine is operating rich, lean, or stoichiometric. In any case, emission control catalysts all serve to eliminate NOx, CO, and NMHC to varying degrees.

The selection of an emission control technology for gaseous emissions depends not only on the targeted pollutants but also the engine type and operating mode, i.e. speed and load. In some instances with rich burn engines, NOx alone may be controlled accompanied by modest, if any, reductions in CO and NMHC. Whereas in the case of stoichiometric and lean burn engines, significant reductions in all three pollutants can be achieved. Table 3 outlines the emission control technologies available for the different engine types.

Table 3: Emission Control Technologies for Stationary IC Engines

Engine Operation	Control Technology	Target Pollutants
Rich	NSCR Catalyst	NOx, CO, NMHC
Stoichiometric	NSCR Catalyst (three-way)	NOx, CO, NMHC
Lean	Oxidation Catalyst (two-way)	CO, NMHC
	Lean-NOx Catalyst	NOx, CO, NMHC
	SCR Catalyst	NOx
	Engine Coating	NOx*, CO, NMHC

*with engine retard

Note: NSCR - nonselective catalytic reduction, SCR - selective catalytic reduction.

Different emission control technologies have to be applied to stationary IC engines depending on their air to fuel ratio. This is due to the fact that the exhaust gas composition differs depending on whether the engine is operated in a rich, lean, or stoichiometric burn condition. Figures 1 through 3 highlight the performance of different catalyst systems for a wide range of air to fuel ratios. Engine operating mode (speed and load) as it affects exhaust gas temperature also has to be considered.

As can be seen in Figure 1, NSCR can achieve substantial NOx reductions for rich burn engines. This same catalyst technology is referred to as a three-way catalyst when the engine is operated at the stoichiometric point (ë=1) where not only is NOx reduced but so are CO and NMHC as shown in the figures. Conversely, lean NOx and oxidation catalysts provide little, if any, emission control in a rich-burn environment. However in a lean-burn environment, oxidation catalysts provide significant reductions in both CO and NMHC, and lean-NOx catalysts provide reductions in NOx, CO, and NMHC. Table 4 outlines the different catalyst technologies available for use on stationary IC engines and the typical reductions that can be achieved (the performance of some catalyst formulations will deviate somewhat from those shown).

Figure 1

CATALYST PERFORMANCE FOR NOx

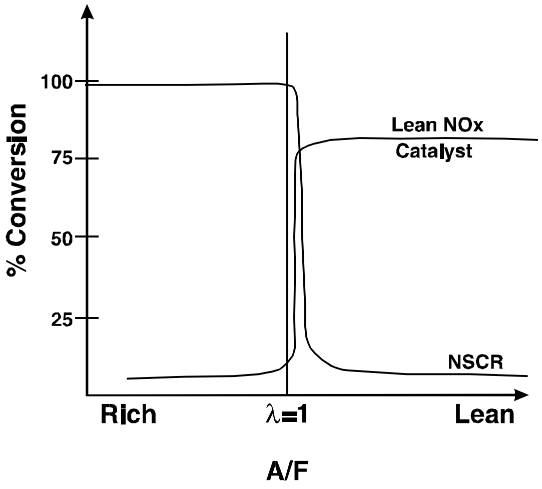


Figure 2

CATALYST PERFORMANCE FOR NMHC

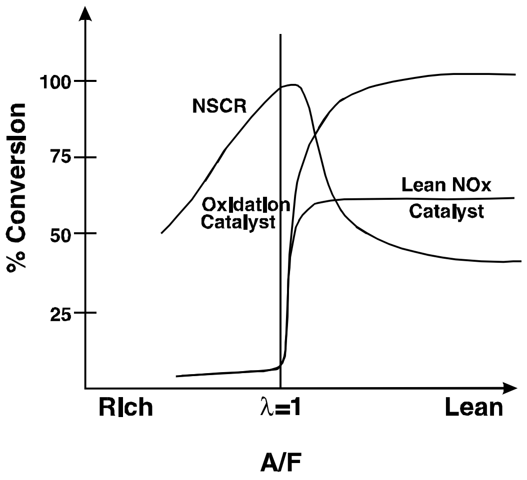


Figure 3

CATALYST PERFORMANCE FOR CO

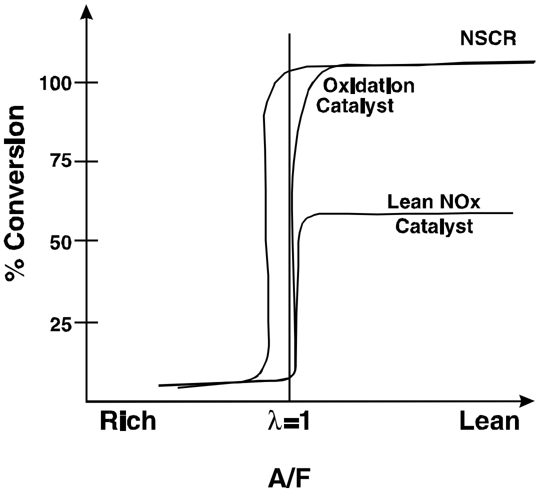


Table 4: Performance of Different Catalyst Technologies

Catalyst Technology	Engine Operation	% Reduction		
		NMHC	CO	NOx
NSCR	Rich	>77	>90	>98
NSCR	Stoich	80	>97	>98
SCR	Lean	minimal	minimal	>95
Oxidation	Lean	>90	>98	n.a.
Lean NOx	Lean	^0	60	>80
Oxidation Catalyst and Engine Coatings*	Lean	60	80	40

Nonselective Catalytic Reduction (NSCR) and Three-way Catalysts. NSCR has been used to control NOx emissions from rich-burn engines for over 15 years. The systems have demonstrated the ability to achieve greater than 98 percent reduction. Over 3000 rich burn IC engines have been equipped with NSCR technology in the U.S. alone. Engines in excess of 250 hp have been equipped with NSCR. In the presence of CO and NMHC in the engine exhaust, the catalyst converts NOx to nitrogen and oxygen.

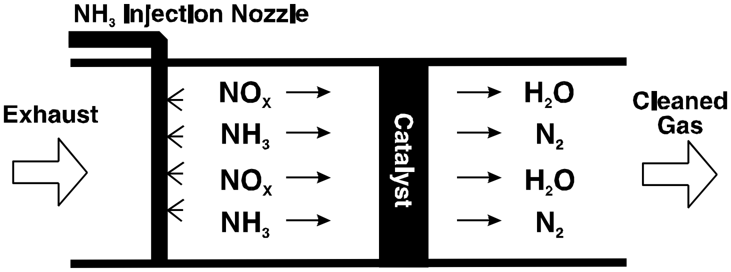
As shown in Figures 2 and 3, NSCR reduces NOx, CO, and NMHC emissions if an engine is operated stoichiometrically. NSCR used in this manner is defined as a three-way conversion catalyst. In order for conversion efficiencies to remain high, the air to fuel ratio must remain within a fairly narrow window of the stoichiometric point (ë=1). NOx conversion efficiency drops dramatically when the engine is run in the lean regime, while NMHC and CO conversion efficiency also declines somewhat. Three-way catalysts are installed on over 1000 stationary IC engines in the U.S. and have been in use for over 10 years.

Selective Catalytic Reduction (SCR). SCR is a method of controlling NOx emissions from lean-burn stationary IC engines. The technology was first patented in 1959 in the U.S. and has been used on over 700 NOx generating sources worldwide, some of which are stationary IC engines. Lean-burn engines are characterized by an oxygen-rich exhaust, thereby making the reduction of NOx virtually impossible using NSCR catalyst technology. However, introducing a reducing agent such as ammonia, urea, or others makes the necessary chemical reactions possible. The reactions that occur over the catalyst bed using ammonia are as follows:

$$4NO + 4NH_3 + O_2 \text{ -----> } 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \text{ -----> } 3N_2 + 6H_2O.$$

Figure 4: Selective Catalytic Reduction



NOx emissions can be reduced by greater than 90 percent. This approach is called selective catalytic reduction (SCR) because with the reducing agent present, the catalyst selectively targets NOx reduction alone. A schematic of a typical SCR system is shown in Figure 4. As shown, the reducing agent is injected upstream of the catalyst bed. The amount of reagent injected is calibrated by measuring the NOx concentration upstream of the catalyst (and possibly downstream) or by its predicted concentration knowing the engine's operating parameters.

Both precious metal and base metal catalysts have been used in SCR systems. Base metal catalysts, typically vanadium and titanium, are used for exhaust gas temperatures between 450°F and 800°F. For higher temperatures (675°F to 1100°F), zeolite catalysts may be used. Both the base metal and zeolite catalysts are sulfur tolerant for diesel engine exhaust. Precious metal SCR catalysts are useful for low temperatures (350°F to 550°F). When using precious metal SCR catalysts, attention should be paid to the fuel sulfur content and the appropriate formulation selected.

Oxidation Catalysts. Oxidation catalysts have been used on off-road mobile source lean-burn engines for almost 30 years. More recently, they have been applied to on-road lean-burn engines as well. In fact, over 350,000 oxidation catalysts were equipped to on-road diesel engines in 1994 alone. In the U.S., over 500 stationary lean-burn IC engines have been outfitted with oxidation catalysts.

Oxidation catalysts contain precious metals impregnated onto a high geometric surface area carrier and are placed in the exhaust stream. They are very effective in controlling CO and NMHC emissions. As previously shown in Table 4, CO can be reduced by greater than 98 percent and NMHC emissions can be reduced by over 90 percent. They are also used to reduce particulate emissions of diesel engines by oxidizing the soluble organic fraction of the particulate - reductions of over 30 percent can be achieved. Oxidation catalysts also serve to eliminate the characteristic odor associated with diesel exhaust by oxidizing the aldehyde and acrolein emissions.

Lean-NOx Catalysts. In anticipation of the on-road heavy-duty diesel engine 4.0 g/bhp-hr NOx standard in 1998 and a further tightening of that standard in 2004, much research and development has been carried out in the area of lean-NOx catalysis. Initial work resulted in catalyst formulations and structures that could reduce NOx emissions in the oxygen-rich diesel exhaust environment. However, durability problems could not be overcome as the structures collapsed within a short period of time. This resulted in further work with both base metal and precious metal catalysts which performed satisfactorily if a small amount of reducing agent was added. For diesel engines, the fuel itself can be used as the reductant.

A small amount of diesel fuel (equivalent to approximately a three percent fuel penalty) can be injected upstream of the catalyst to provide the additional hydrocarbons needed to significantly reduce NOx emissions. At the same time, CO and NMHC emissions are reduced dramatically. Although a relatively new technology, one stationary diesel engine has been equipped with a lean-NOx catalyst and NOx emissions are being reduced by 80 percent, CO by 60 percent, and NMHC emissions by 60 percent.

Maintenance of Catalysts for Stationary IC Engines. Whether employing NSCR, SCR, oxidation, or lean-NOx catalytic controls on an IC engine, there are conditions which can reduce catalytic activity. Catalytic deactivation may result from (1) chemical poisoning, (2) masking, or (3) thermal sintering. All three can take place slowly; the process is often called "aging". Thousands of stationary IC engine catalyst applications have been effectively used for stationary IC engine gaseous emission control for five years or more. Some installations, however, do experience performance loss over time. In most of these cases, the reduced performance results from the catalyst being masked by contaminants in the exhaust. Catalyst manufacturers can test such a catalyst, taking a sample from the lower-performing unit to determine the cause of the activity loss and the best method of regeneration. Cleaning procedures can remove contaminants from the catalyst, usually restoring catalytic activity.

Chemical poisoning of a catalyst can be either temporary or more permanent. A temporary poison is one like oxides of sulfur which inhibits optimum catalyst performance, but such loss is recovered by exposure to temperatures above 400°C. In many instances, chemical poisoning can be reversed with special procedures. Poisoning is less of a concern with today's high technology catalysts, many of which are formulated to have a degree of poison resistance.

Thermal sintering of the catalyst is not reversible because it causes a collapse of the washcoat. However, overtemperature control can be incorporated into the system to prevent this from happening. Also, high temperature catalysts have been developed with components resistant to >1000°C for some applications.

In order to ensure continued high catalyst performance, manufacturers often recommend a maintenance program. Components of the program include overtemperature monitoring and control, as mentioned above; specifying a maximum pressure drop across the catalyst; lubricating oil specifications to prevent poisoning; catalyst washing procedures; emissions monitoring; and laboratory catalyst evaluations. Following the manufacturer's recommendations will ensure maximum catalyst life and performance.

Ceramic Engine Coatings

Ceramic engine coatings have been used for almost 5 years in well over 200 stationary and mobile diesel engines. The primary motivation has been to reduce carbon soot, or visible smoke. However, recent testing has shown that when used in diesel engines, engine coatings in combination with an oxidation catalyst will allow the engine timing to be retarded such that NOx emissions are reduced by 40%, with decreases in NMHC and CO.

Work is currently under way on ceramic coatings in combination with other technologies which may lead to even further PM reductions and NOx levels below a 4.0 g/bhp-hr for both on road and stationary heavy duty diesel engines.

In the case of gaseous fuels, ceramic coatings have shown the ability to allow the user to operate their engines with timing significantly advanced generating higher power levels. Also wider ranges of fuel composition and ambient air changes are tolerated without the deleterious effects of precombustion. Tests are currently underway to understand the effects of the coatings on specific emissions from gaseous fueled engines.

Costs of Emission Control of Stationary IC Engines

Table 5 outlines the approximate costs the different catalytic controls available for IC engines.

Table 5: Cost of Catalytic Control Technologies

Catalyst Type	$/bhp
NSCR	10-12
SCR	50-125
Oxidation	9-10
Lean NOx	10-20
Engine Coatings	5-12

IV. PARTICULATE EMISSION CONTROL OF STATIONARY IC ENGINES

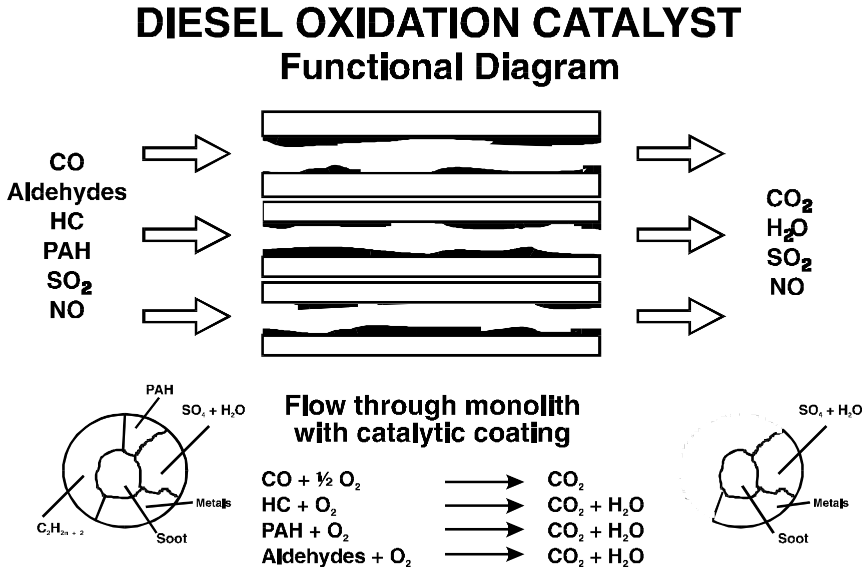
Particulate matter (PM) emission control of stationary IC engines is a concern for diesel engines which emit a relatively high amount of particulate compared to engines using other fuels. Diesel particulate emissions are composed of a variety of compounds from fuel and lube oil combustion, as well as engine wear and sulfate from diesel fuel sulfur. The majority of the particulate consists of carbon and the soluble organic fraction (SOF) consisting of unburned fuel and unburned lube oil. Both oxidation catalysts and diesel particulate filters can be used to substantially reduce diesel PM emissions.

Diesel Oxidation Catalysts

Recently, a catalyst system has been approved with EPA's urban bus retrofit/rebuild program. The program requires that particulate emissions be reduced by at least 25 percent. Other investigations reported in SAE papers substantiate that 25 percent PM reductions are easily achieved. SAE Paper No. 900600 reported that catalysts will reduce 90 percent of the SOF resulting in a 40 to 50 percent reduction in total PM emissions.

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.

Figure 5



As for gaseous emission control, the cost of using an oxidation catalyst for PM control is approximately $9-10/bhp. As noted earlier, Oxidation catalysts have been used on off-road mobile source lean-burn engines for almost 30 years. More recently, they have been applied to on-road lean-burn engines as well. In fact over 350,000 oxidation catalysts were equipped to on-road diesel engines in 1994 alone. In the U.S., over 150 stationary diesel engines have been outfitted with oxidation catalysts.

Ceramic Engine Coatings

Ceramic engine coatings have been proven to reduce carbon soot. Recent tests for EPA certification show about 50% reduction in opacity. This reduction results because of the change in combustion characteristics in the cylinder. Additionally, this reduction in carbon soot results in about a 30% reduction in PM. When used in combination with diesel oxidation catalyst, the overall PM reduction increases to about 35%.

Ceramic engine coatings were found to improve fuel economy by 7% in a 4-year demonstration conducted by a U.S. transit authority. With over 100,000 miles on some buses participating in the study, engine parts were removed that showed no wear or deterioration of the engine coatings.

Diesel Particulate Filters (DPF) or Trap Oxidizer System

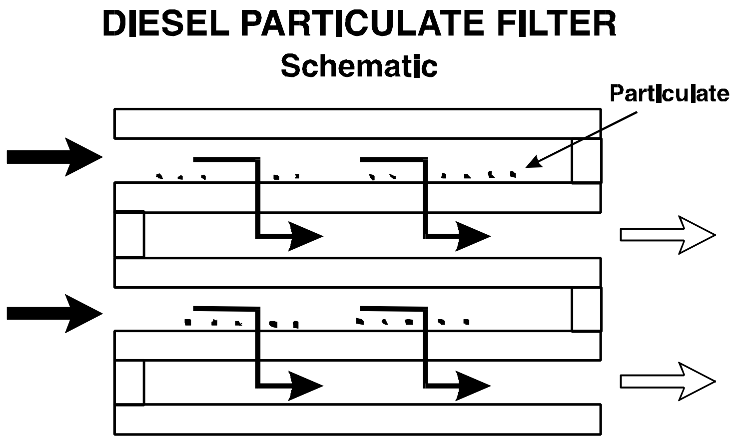
The trap oxidizer system consists of a filter positioned in the exhaust stream designed to collect a significant fraction of the particulate emissions while allowing the exhaust gases to pass through the system. Since the volume of PM generated by a diesel engine is sufficient to fill up and plug a reasonably sized DPF 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 DPF of collected particulate.

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, woven silica fiber coils, ceramic foam, mat-like ceramic fibers, wire mesh, and sintered metal substrates. Collection efficiencies of these filters range from 50 percent to over 90 percent.

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 6



Particulate-ladened 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.

For example, 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 DPF or catalyst soot filter. The application of a base or precious metal coating applied to the surface of the DPF reduces the ignition temperature necessary for oxidation of the particulate so that the collected particulate is spontaneously ignited at a temperature of ~375° (a condition often achieved in 4-stroke engine exhaust). Regeneration is achieved without the use of a burner or heater.

- 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 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.

- 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.

- Using ceramic engine coatings, which will increase the exhaust temperature, thereby increasing the time the exhaust temperature exceeds the required regeneration temperature.

Some combinations of the above are also possible.

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 designed for 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.

Learning from the experience gained from these first generation systems, manufacturers are now focusing 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.

Using *improved catalyst coatings* to facilitate regeneration is an attractive option, particularly for four-stroke engine applications where exhaust temperatures are typically higher than with two-stroke engines. A catalytic coating applied to a properly designed DPF can combine the best features of both types of control technologies. One manufacturer uses a combination of a catalyst in front of a filter to convert NO to NO_2 to significantly reduce the temperature required for regeneration. Both systems are simple and have achieved excellent results in field demonstrations.

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, 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 PM. This occurs at reduced temperatures relative to the temperature required for ignition in the absence of fuel additives. It is this principle 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, additive manufacturers have noted that in some instances, combustion may be improved.

Although most trap systems have been applied in mobile source applications, there has been some use for stationary source IC engines. Over thirty systems have been in use for over three years in Europe. These systems use a fuel burner for regeneration. Indeed, stationary source applications are well suited to trap-use in that the engines normally operate at a given load and speed settings. Thus, there is a predictable exhaust temperature, making the selection of the optimum technology an easier task. Depending on engine size, the cost of trap oxidizer system technology ranges from approximately $30-$50/bhp.

Maintenance of Diesel Particulate Filters or Trap Oxidizers. Given the limited use of trap oxidizers for stationary IC engines currently, maintenance procedures are not well documented. Nonetheless, the components of a maintenance program could include:

- measuring pressure drop across the trap compared to a speed/load map to ensure it does not exceed design limits,

- measuring inlet exhaust gas temperature to ensure it does not drop below the regime the regeneration system was designed for,

- measuring inlet and outlet exhaust gas temperature during regeneration to ensure these are within design values,

- measuring opacity to be compared to a baseline to ensure trap core integrity.

As residual, noncombustible particles build-up in the trap, the backpressure of the system will increase. Pressure drop measurements should be used to ensure that engine manufacturer's specifications are not exceeded. Techniques have been developed for certain systems and others continue to evolve for removal of the accumulated material. This should be performed as needed.

V. USE OF CATALYST AND PARTICULATE FILTER CONTROL IN CONJUNCTION WITH OTHER CONTROL STRATEGIES

Retarding injection timing slightly or incorporating exhaust gas recirculation (EGR) will reduce NOx emissions of diesel engines by more than 40 percent. However, both techniques are accompanied by secondary effects. Injection timing retard, while decreasing NOx emissions substantially, increases the emissions of CO, NMHC, and PM and reduces fuel economy. The increase in the other exhaust emissions, however, can be offset with either oxidation catalyst or diesel particulate filter technology. Ceramic engine coatings have been found to offset the fuel economy penalty as well. Employing EGR to diesel engines introduces abrasive diesel particulate into the air intake which could result in increased engine wear and fouling. Using EGR after a diesel particulate filter would supply clean EGR and effectively eliminate this concern.

VI. CONCLUSIONS

- A variety of emission control technologies exist for controlling NOx, CO, NMHC, and PM emissions from stationary IC engines and have been in use for 10 years.

- Oxidation catalysts provide significant reductions in CO (90%) and NMHC (90%) from lean burn engines at a cost of $9-10/bhp. In the case of diesel engines, PM emissions are also reduced by greater than 25 percent with no additional cost.

- NSCR can be used to eliminate greater than 90 percent of NOx emissions from rich burn engines for $10-15/bhp.

- NSCR, or three-way catalysts, eliminate over 90 percent of NOx, CO, and NMHC for engines operated stoichiometrically at a cost of $10-15/bhp.

- SCR can be used to reduce greater than 90 percent of NOx emissions from lean burn engines at a cost of $50-125/bhp.

- More recently, lean NOx catalysts have been applied to stationary lean burn IC engines to provide significant reductions in NOx (80%), CO (60%), and NMHC (60%) at a cost of $10-20/bhp.

- Although not currently in wide spread use on stationary engines, diesel particulate filters or trap oxidizers provide considerable potential to eliminate more than 90 percent of the PM emissions from stationary diesel engines at a cost of $30-50/bhp depending on engine size. Catalytic coatings on such DPFs add the advantage of also reducing CO and HC.

- Ceramic coatings used on the internal combustion surfaces of IC engines can improve performance, reduce emissions or allow a trade off in performance and emission levels not possible using catalyst technology itself. Used in conjunction with catalyst, ceramic coatings have allowed significant reductions in PM and NOx for heavy duty diesels while providing significant performance increases in power and torque. Costs are in the range of $5-15/bhp. Improved fuel economy offsets the cost of the coating.