II. DIESEL OXIDATION CATALYST (DOC)

A. Technology Overview and Description

OVERVIEW

DOCs have been in commercial use since the late 1960s in offroad applications and since the 1980s in on-road applications. This technology has a proven track record of excellent performance. In on-road OE applications, over 50 million passenger cars and over 3 million trucks and buses have been equipped with DOCs. Worldwide, over 200,000 trucks and buses have been retrofitted with DOCs. In addition, over 250,000 new and existing offroad engines have been equipped. DOCs have the greatest application experience of any retrofit strategy, having been installed on trucks, buses, passenger cars, and offroad equipment including mining equipment, construction equipment, utility equipment, locomotives and marine vessels. Retrofitting engines with DOCs is extremely popular since the technology has near universal application. It is easily installed, requires virtually no maintenance, does not adversely impact vehicle performance or fuel consumption, achieves emission reductions in a cost-effective manner, and can operate effectively on fuels with 500 ppm sulfur and higher depending on the application and the pollutant(s) to be controlled.

DOCs control PM exhaust emissions by 20% to 50% depending on the engine exhaust temperature, the sulfur level in the fuel, the composition of the engine-out PM, and other factors. This technology also controls HC and CO up to 90%, as well as reducing diesel smoke and virtually eliminating diesel odor. Also, in cases where DOCs are used as a muffler replacement, the noise attenuation of the DOCs meets or exceeds the specification of the OE muffler being replaced. DOCs in both on-road and offroad applications have demonstrated high emission reduction performance over extended periods. DOCs routinely last the remaining life of the engine.

Problems with DOCs have been very rare. Where they have occurred, they tended to involve such issues as improper DOC design configuration for a particular vehicle/equipment application or failure to provide the correct installation hardware. These types of issues can be easily addressed by close coordination and planning between the DOC supplier and the vehicle/equipment fleet personnel. DOC plugging has occurred on very rare occasions and typically involved older (pre-1990), high oil consumption engines that may operate at idle for expended periods of time and/or operate in areas with very cold ambient temperatures. Potential problem vehicles can be rejected for DOC retrofit, engines can be rebuilt, or the vehicle/equipment repowered. Also, backpressure monitors can be installed if there is a risk of PM accumulating on the catalyst substrate leading to engine backpressure increase.

Decades of experience indicate that DOCs do not have any adverse impacts on engine performance. With regard to fuel economy, studies conducted over the years generally have reported that either DOCs have no impact on fuel economy or in those cases in which a slight decrease was measured, it was not statistically significant.

Several DOC designs have been verified by EPA and CARB for on-road and to a limited extent for offroad applications (see www.epa.gov/otaq/retrofit/retroverifiedlist.htm, and

www.arb.ca.gov/diesel/verdev/verdev.htm). The PM soluble organic fraction (SOF) from a diesel engine is related, in part, to the engine lubricant consumption and in-cylinder combustion characteristics of that diesel engine. DOCs can be used in combination with other technologies including, FBCs, DPFs, LNCs, SCR and CCV systems. DOCs also have been used in combination with engine modification kits that reduce NO_x emissions. This latter technology combination was used, for example, in the EPA urban bus retrofit/rebuild program in the early 1990s.

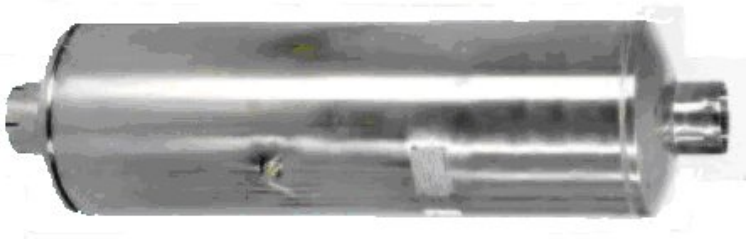
The overall experience with DOCs in retrofit applications during the past 30 years has been outstanding. This technology has been the most popular retrofit choice to date because of several factors including:

- Virtually universal application.
- Easy installation.
- No technology maintenance.
- Ability to be used on vehicles/equipment fueled with conventional diesel fuels.
- Lower cost compared to other retrofit technologies.
- No operational issues, impacts on vehicle/equipment performance or impacts on fuel consumption.

TECHNOLOGY DESCRIPTION

A typical DOC is a stainless steel canister installed in the exhaust system much like a muffler. The canister contains a catalyst support or "substrate" on which the catalytic material is coated. These substrates are typically ceramic or metallic honeycomb-shaped or, in some cases, wire mesh. The substrate is coated with a catalytic formulation, which includes precious metals such as platinum and palladium. There are no moving parts, just a large amount of surface area coated with the catalytic formulation. As the exhaust gas passes through the substrate, the SOF, CO, and HC are chemically oxidized to form CO_2 and water. In some instances, PM exhaust emissions of a vehicle/equipment are extremely high, as can occasionally be an issue with some larger, older offroad engine. In those cases where high levels of PM are emitted and there is some concern that the DOC could plug, a backpressure monitor can be installed. Figure 2-1 is an example of a commercially available muffler replacement-style DOC for retrofit applications.

Figure 2-1, Muffler Replacement DOC



B. Emission Reduction

A DOC reduces engine-out unburned HCs, toxic HCs CO by up to 90%, and exhaust PM by 20% to 50% depending on exhaust temperature, sulfur level in the fuel, composition of engine-out PM and other factors. DOCs control the SOF of the PM by up to 90%. The PM SOF from a diesel engine is related, in part, to the engine lubricant consumption and in-cylinder combustion characteristics of that diesel engine. Older engines with higher lubricating oil consumption typically emit a high fraction of SOF and as a result the DOC will reduce a greater percent of total PM than would be achieved on a newer engine with a lower percentage of SOF. Older offroad engines typically have a higher concentration of SOF compared to new on-road vehicles, making DOCs a particularly effective application for these offroad engines. Since DOC technology is designed to control the SOF of the PM, the technology is not effective in reducing the carbon-based particles, including the ultra-fine fraction. DOCs do not impact the level of NO_x emissions and, since DOCs typically do not adversely impact fuel consumption, they do not affect the level of CO_2 emissions.

DOCs also reduce smoke emissions from older vehicles by over 50% and virtually eliminate the pungent odor associated with diesel engines. Also, the noise attenuation achieved by a DOC is equal to, and some cases exceeds, the performance of the OE muffler may replace.

DOC performance is not reduced significantly when used with conventional low sulfur content (up to 300 ppm to 500 ppm) diesel fuel. However, the amount of sulfate, and in turn the amount of total PM measured will increase as the sulfur content increases. Consequently, the emission control performance of a DOC is enhanced if it is operated with ultra-low sulfur diesel fuel (ULSD) with a maximum sulfur content of 15 ppm.

C. Status and Availability

Commercial application of DOC technology has spanned over 30 years. The technology has been successful applied and operated extremely effectively on a broad range of on-road and offroad applications. As noted above, with on-road OE applications over 50 million passenger cars in Europe and over 3 million trucks and buses in the U.S. alone have been equipped with DOCs. Worldwide, over 200,000 trucks and buses have been retrofitted with DOCs. DOC retrofit kits for passenger cars have been commercially available since the early 1990s. In addition, over 250,000 new and existing offroad engines have been equipped with DOCs.

ON-ROAD VEHICLE DOC RETROFIT STATUS

Numerous DOC retrofit projects have been conducted throughout the world involving trucks and buses. For example, Hong Kong has implemented DOC retrofit programs involving 40,000 medium duty trucks and 2,000 transit buses. In Mexico, over 8,000 heavy-duty vehicles were retrofitted with DOCs. Under the U.S. EPA urban bus retrofit/rebuild program, over 15,000 transit buses were retrofitted with DOCs. In the U.S. over 250 individual school districts have implemented or will soon implement DOC retrofits on school buses. Other U. S. programs currently underway are applying DOC retrofits to school buses, transit buses, freight and delivery vehicles, refuse trucks and utility vehicles.

OFFROAD EQUIPMENT DOC RETROFIT STATUS

As noted above, DOCs have been retrofitted on offroad equipment for over 30 years and this technology has been equipped on over 250,000 offroad engines. The types of offroad equipment retrofitted with DOCs includes mining equipment (e.g., excavators), construction equipment (e.g., skid steer loaders, dump trucks, rubber tire loaders, excavators), materials handling equipment (e.g., forklifts), utility equipment (e.g., street sweepers, tractors), agricultural equipment (e.g., irrigation pumps), and marine vessels (e.g., passenger ferries). DOCs have been used on offroad engines ranging from less than 75 hp (e.g., forklifts) to over 750 hp (e.g., large passenger ferries in Hong Kong and large stationary engines in California).

Two U.S. programs involving larger scale DOC retrofit on offroad equipment are the Massachusetts Central Artery/Tunnel Project (the “Big Dig” project) in Boston, Massachusetts and the I-95 New Haven Harbor Crossing Corridor Improvement Program (Q-Bridge Project) in New Haven, Connecticut (See Volume 1, Section III.B. for more information about these programs). Over 200 pieces of construction equipment were retrofitted with DOCs as part of the Big Dig project and nearly 100 DOC retrofits on construction equipment on the Q Bridge project.

AVAILABILTY

Retrofit DOCs are readily available from several technology and product suppliers. Appendix D contains a list of suppliers. As noted previously, products are available in a variety of engine size ranges and configurations, including muffler replacements and add-on products. Custom-configured units can also be provided by several suppliers.

D. Selection and Use Criteria

With very limited exceptions, DOC technology can be applied to virtually any type and size of diesel-powered engines. As noted above, DOCs have been applied to a wide range of on-road and offroad diesel engine applications. The only potentially limiting factors are 1) available space on the vehicle or equipment, 2) older engines with extremely high PM emissions levels (e.g., pre-1990 model year), 3) very cold exhaust temperatures (below 200°C such as were vehicles/equipment operate in extremely cold ambient temperature conditions and idle for extended periods), and 4) vehicles that operate on diesel fuels with substantially higher than 500 ppm sulfur levels.

AVAILABLE SPACE

In almost every instance in which a DOC retrofit was contemplated, available space was found to equip the technology. However, it is possible that situations will arise where the available space is not sufficient to insure proper installation and performance of the DOC or to avoid interference with vehicle/equipment operation. For that reason and in those rare applications where available space may be an issue, an inspection of the vehicle/equipment by the technology provider and coordination between the technology provider, the vehicle/ equipment operator, and, where appropriate, knowledgeable staff of the engine manufacturer distributor.

HIGH PM EMITTING VEHICLES/EQUIPMENT

If the engine-out PM is too great, it possibly could plug the DOC. This rarely has been an issue, but it can occur with older, high-oil consumption engines (e.g., two-stroke engines), particularly on engines with large horsepower ratings. For example, a DOC installed on an older locomotive with a two-stoke, 3,000 hp engine that had high-oil consumption and was operated at idle for extended periods plugged the DOC in a matter of weeks. Where extremely high PM emissions are an issue, it may be best to reject the applications or to have the vehicle/equipment repowered. Also, DOCs with large substrate cell sizes can be utilized to reduce the impacts of higher PM emissions. Where there is concern about PM build-up on the surfaces of the DOC substrate, backpressure monitors can be installed.

EXTREMELY LOW EXHAUST TEMPERATURES

To function properly, a DOC needs exhaust temperatures that are above 200°C. On rare occasions, problems have occurred with the failure to achieve the minimum temperatures needed for the DOC to function effectively. This problem has occurred in the past on occasion when a vehicle is operated in very could climates (e.g., Alaska during the winter) and the vehicle/equipment idled for extended periods (e.g., up to two days). If any question exists regarding whether the vehicle/equipment may not achieve adequate exhaust temperature, temperature traces can be measure over the expected operating cycle under the worst ambient temperatures expected. Also, insulation can be installed in the exhaust system upstream of the DOC to help retain exhaust temperatures reaching the DOC.

E. Installation and Vehicle Modifications

As noted above, DOC technology has virtually universal application, installation typically is very straight-forward and maintenance is rarely, if ever required. Nevertheless, care should be taken in: 1) selecting and preparing vehicles/equipment for retrofit, 2) installing the DOCs, and 3) periodically checking the DOC, the installation hardware and the exhaust system for physical damage.

PRE-INSTALLATION PROCEDURES

Even though DOCs can be readily retrofitted on virtually all types of vehicles and equipment, a screening process should be conducted. First, it should be determined whether the vehicle is already equipped with a DOC. All transit buses sold beginning with the 1994 model year were equipped with DOCs and certain light and heavy-duty trucks and school buses have DOCs installed as original equipment. Unfortunately, a comprehensive list of engine/vehicle models does not exist, nor will a visual examination of the exhaust system always provide an answer. The technology supplier may have some information, but the best way to determine is to check the muffler part number. If it is an OE DOC/muffler it will have a special part number.

Vehicle/equipment with engines that have excessively high lubricating oil consumption, have a history of mechanical problems, or are nearing retirement are not good candidates for DOC retrofit. Also, vehicles/equipment with very low operating temperatures such as those that will operate at idle for very long periods and/or operate in extremely cold ambient temperatures may not be good candidates.

Prior to installation, both the engine and exhaust system should be inspected for any worn parts or leaks. Any routine or necessary maintenance should then be performed. Performing needed maintenance not only will prepare the engine for DOC retrofit, but it could also improve fuel economy and vehicle/equipment performance.

INSTALLATION AND VEHICLE MODIFICATIONS

DOC installation is very straightforward and most often the DOC is installed as a direct replacement for the existing OE muffler. Installation typically takes one to two hours and is often performed by fleet personnel. At least some training by the DOC provider is beneficial. The DOC can also be installed as a direct fit in the exhaust system, including as a direct fit close-coupled to the manifold. For direct fit applications, the retrofit installation is frequently performed by, or in close consultation with, the DOC supplier.

Muffler designs and the length of inlet and outlet exhaust pipes can vary greatly. Given the breadth of experience with DOC retrofits, the DOC provider in many cases will have pre-fabricated DOC/piping designs available. In those instances where prefabricated designs are not available, the technology provider should inspect the vehicles or in some other manner (e.g., scale drawings) obtain the necessary information on the dimensions and connecting piping to ensure a proper retrofit. The retrofit kit should also contain the appropriate installation hardware (e.g., hangers) or, at the least, instruction regarding the appropriate installation hardware that should be used by the vehicle/equipment fleet personnel.

Over the past several years, delays in DOC deliveries, often substantial at times, have been experience in the U.S. due to industry-wide shortages of catalyst substrates. This shortage was caused by a rapid increase in demand worldwide for both DOC substrates and DPF filters. The supply shortage seems to be improving and increased manufacturing capacity has been brought on line. Nevertheless, the possibility of delays should be factored into plans to meet retrofit project schedules – the more lead time allowed for delivery, the greater the chance the retrofits can be completed on schedule.

F. Fuel Requirements

While maximum DOC performance can be achieved with diesel fuel containing less than 15 ppm sulfur, DOCs have performed effectively on vehicles/equipment fueled with diesel fuel up to 500 ppm sulfur content. DOCs have also been installed on vehicles/equipment that contain more than 500 ppm sulfur content. DOC performance on fuels with a higher sulfur content will vary depending on the catalyst formulation, engine type, and duty cycle. In cases in which the goal is to reduce PM, as opposed to HC or CO, diesel fuel with less than 500 ppm sulfur content is recommended.

G. Maintenance

As noted above, DOCs typically do not require any maintenance. Nevertheless, the DOC, the installation hardware and the exhaust system should be visually inspected periodically for physical damage or deterioration. In situations in which there has been an engine malfunction, such as faulty injectors or the vehicle/equipment emits high levels of PM, it is advisable to determine if catalyst substrate plugging is occurring. In those extremely rare instances in which ash and other materials accumulate on the surfaces of the DOC substrate causing an engine backpressure increase, the DOC can be removed and cleaned using methods like those employed in cleaning DPFs (See Volume 2, Section III).

H. Costs

In 2000, CARB estimated the expected cost of DOC technology by horsepower rating as shown in Table 2-1 below.

Table 2-1, CARB-Estimated Costs of DOC Technology

Engine Horsepower	Hardware Cost
40	$400 - $600
100	$680 - $1,356
275	$2,100 - $3,700
400	$2,800 - $3,700
1,400	$10,000 - $20,000

More recent estimates, suggest the costs for DOCs in retrofit applications are decreasing slightly and range from less than $500 to $1,250 for engines in the 100-200 horsepower category, and from less than $1,000 to $1,750 for engines in the 200-500 horsepower category. Costs can vary

depending on such factors as: 1) whether the DOC was installed as a separate device ("direct fit") in the engine exhaust or a muffler replacement and 2) the number of DOCs being purchased. The cost of DOC technology may continue to decline as the volume for DOC substrates (and DPF filters) increases providing economies of scale in production.

DOC installation typically takes one to two hours and if provided by the technology supplier or its agent, the cost is in the range of less than $100 to about $200. Since, DOC installation is relatively straightforward, fleet technicians, sometimes after receiving training from the DOC supplier, install the DOCs themselves, thereby avoiding external installation costs. Finally, since DOCs are virtually maintenance free except for periodic checks of the DOC and exhaust system for mechanical integrity, typically no maintenance costs are incurred.