III. DIESEL PARTICULATE FILTER (DPF)

A. Technology Overview and Description

OVERVIEW

DPFs are commercially available and used both as original equipment (OE) on passenger cars in Europe and on transit buses in the U.S. and elsewhere. Also used as a retrofit technology, DPFs are found on a variety of on-road and offroad vehicles and equipment. DPFs have demonstrated the capability to reduce PM by up to 90% or more, and those DPFs that employ a catalyst component are capable of reducing HC and CO by up to 90%. DPFs also reduce or eliminate smoke and odor from a diesel engine. DPFs do not impact NOx emissions and most DPF designs have little or no measurable impact on fuel consumption. Overall, the performance record for DPFs has been quite good. Some technology and application-related problems and failures have arisen, but as application experience grows and improvements to the technology are made, the instances of problems continue to decline. A relatively new development is the emergence of flow-through filters that have a lower PM mass control efficiency compared to conventional DPFs, but have the potential for wider vehicle/equipment applications.

DPF technology is application specific. This means that before the technology can be applied to a given vehicle or piece of equipment, certain prerequisites most be met. Considerable care is needed in determining whether a DPF is a good fit for a particular application (See “Selection and Use Criteria”, below). DPFs also require more maintenance and performance monitoring than other technologies such as DOCs.

Several DPFs have been verified for on-road applications and limited offroad applications by both EPA and/or CARB (see www.epa.gov/otaq/tretrofit/retroverifiedlist.htm, and www.arb.ca.gov/diesel/verdev/verdev.htm). In retrofit applications, DPFs can be combined with NOx control technologies such as lean NOx catalysts, SCR technology and low-pressure EGR systems to provide significant PM and NOx emission reductions.

DPFs are often categorized as either “passive” or “active” depending on the method used to achieve filter regeneration. A passive DPF is one in which the filter regenerates in normal vehicle/equipment operation without any additional assistance. Examples of passive DPFs are filters coated with a catalytic material, a diesel oxidation catalyst upstream of the DPF, and a FBC used in combination of a filter. An active DPF system relies on additional strategies to ensure that filter regeneration occurs. Examples of active DPFs are ones that employ engine modifications, fuel injection, on-board burners or heaters, or off-board electrical heaters.

The advantages of passive systems are that they are technologically less complex, require far less servicing, and are less expensive than active systems. The advantage of active systems is that they will function effectively even if the desired exhaust temperatures are not achieved in normal operation and consequently can be employed in applications (e.g., vehicles/equipment with low exhaust temperatures) on which passive filters cannot used.

In the U.S., most retrofit applications have employed passive systems, while in Europe both passive and active DPF systems have been widely used. Looking to the future, a combined strategy of catalyst-based filters plus an active component such as fuel injection will be used to meet the EPA 2007 and later model year on-road heavy-duty truck standards. Catalyst-based filters with an active component could also emerge in retrofit applications.

The overall experience with both active and passive DPFs in both on-road and offroad applications has been very good. When properly constructed, applied, maintained, and fueled, DPFs have demonstrated high PM control efficiencies for extended periods. For example, studies have reported that DPFs: 1) on trucks have performed effectively for up to 350,000 miles or more, 2) on offroad applications have performed effectively for up to 15,000 hours or more in rugged work environments, and 3) on locomotives have performed effectively for over 400,000 kilometers without any reported problems. In those instances were applications of passive DPFs were successful in terms of emission control performance, system durability, and minimum maintenance, several common factors were present, including:

- Newer, well-maintained engines with low engine lubricating oil consumption.
- Engines fueled with ULSD.
- Operating exhaust temperature profiles were well above the minimum time/temperature specified by the technology provider.

Occasionally, problems have arisen with DPF applications/operations but the instances of problems have declined over time as experience has been gained in properly selecting applications for retrofit and DPF design improvements have been made. For example, the Switzerland construction equipment retrofit program was initiated in 1998 and resulted in over 7,000 engines being equipped with either active or passive DPFs. As a result, this program had a failure rate of only 2% in 2003 (down from 10% in 1998 and 6% in 2000). Program officials predict that in the near future the failure rate will drop well below 1%.

DPF problems and failures have occurred in both pilot and full-scale commercial programs. In pilot programs, which typically are conducted to test and even “push” the limits of the technologies, applications and fuel sulfur levels, problems and failures are expected to be part of the process. In commercial applications, problems, where they have occurred can be traced to several recurring issues. The most frequent problem associated with DPF technology is the plugging of the filter with PM, which in some cases resulted in a filter failure. A secondary problem was the occasional malfunction of the backpressure alarm or the electronic diagnostic system. The causes of filter plugging/failure include the following:

- Inadequate exhaust temperatures to support filter regeneration.
- Improper filter sizing for a specific application.
- Engine component wear or failure.
- Fueling with diesel fuel with too high a sulfur level.

- Incomplete filter cleaning.
- DPFs that were installed on OE engines with high-pressure EGR systems.

Adequate Temperatures to Support Filter Regeneration – For passive DPF systems, which depend on a minimum exhaust temperature profile for filter regeneration, the failure to achieve adequate temperatures in actual operation is the major cause of premature filter plugging, filter failures, and vehicle/equipment operational problems. Problems with filter plugging have occurred even when data logging was performed and the exhaust temperatures were consider adequate to support regeneration. In those cases, the problem can be traced to the fact that the vehicle/equipment operating cycle did not represent the "worst-case" operating cycle in terms of engine speed, engine load, and idling time.

Improper Filter Sizing – If the filter size in terms of volume is inadequate to properly collect and destroy the PM as required, premature plugging can occur. This problem can be fixed by increasing the volume of the filter, typically by increasing the filter diameter. For example, a fleet of transit buses operating in Washington State experienced some problems with premature filter plugging. When the original filter, which had a diameter of 9 inches was replaced with a filter with a 10.5-inch diameter, the filter cleaning intervals were extended to once a year or longer. Of course, care must be taken to ensure a DPF with a larger filter volume can be properly fitted to the vehicle/equipment.

Engine Component Wear or Failure – Engine component wear or failure can cause excess fuel or lubricating oil to be introduced into the engine combustion process resulting in excess PM created and collecting on the filter. This increased level of PM can result in the total amount of PM collected on the filter to exceed the capacity of the filter's ability to destroy the PM. This in turn will cause premature filter plugging. For example, worn fuel injectors in some cases can drip enough fuel into the combustion chamber that the resulting increase in PM emissions can cause premature filter plugging. If a turbocharger failure occurs, it can very quickly result in filter plugging.

DPF Cleaning – Proper DPF cleaning can restore the filter to virtually the same or near the same pressure drop through the filter. However, if the filter cleaning procedure is not performed correctly or is not the appropriate method given the nature of the constituents collected on the filter, residue will remain on the filter. As a result, the pressure drop through the filter will not be restored to original levels, and thus will shorten the interval until the next filter cleaning is required. For example, in some instances cleaning by using compressed air alone may not be sufficient to clean the filter. In those cases, the compressed air procedure should be used in combination with heat treatment.

Problems with OE High-Pressure EGR-Equipped Vehicles – Several transit bus projects in the U.S. have reported problems with OE DPFs equipped with high-pressure EGR systems on new engines . The problem is an issue of systems integration. Work is underway to better understand the causes of the problems and to develop appropriate technological fixes.

Using Diesel Fuel with Inappropriate Sulfur Levels – The sulfur level in diesel fuel can adversely impact the performance of catalyst-based DPFs. This includes adversely impacting the filter regeneration process that can lead to filter plugging. Catalyst-based DPFs operate most effectively with ULSD (less than 15 ppm sulfur) although this technology has been applied occasionally in applications where the fuel had a sulfur content of less than 30 ppm and in rarer instances where the sulfur content was less than 50 ppm. Fuel sulfur-related problems can occur under several situations where: 1) vehicles/equipment are intentionally or inadvertently fueled with diesel fuel containing higher than recommended levels, 2) the fuel is contaminated during the delivery process or in the storage facilities, or 3) the fuel sulfur levels recommended by the technology provider proved to be too high to support proper filter regeneration.

On occasion, vehicle use or service has been interrupted because of malfunctions of the exhaust backpressure sensor, the exhaust temperature thermocouple and/or the control software module which signaled a problem when no problem actually existed. These malfunctions have been attributed to such things as the sensitivity of the backpressure measurement probes and the need to better optimize the diagnostic systems to operate effectively in a given vehicle/equipment operating application. The technology providers have developed improved systems to address these issues.

As experience with DPFs has grown, knowledge has been gained regarding better application of the technology. This includes more informed decisions regarding the appropriate vehicle/equipment candidates for a DPF retrofit, including improved predictive capability modeling. It also includes using better application designs, including appropriate filter sizing and where needed, using insulation on the exhaust pipe between the engine and the inlet of the DPF, and/or around the DPF itself.

In addition, technological improvements have been made to the DPF system design to reduce the possibility of problems. These include:

- Improvements to catalyst-based DPF system designs and catalytic formulas to initiate filter regeneration at lower operating temperatures.
- Improvements in the catalytic formulations of catalyst-based DPFs to make them less sensitive in creating sulfates.
- Improvements in filter designs to be more resistant to ash build-up.
- Improved monitoring and diagnostic systems.
- Improved filter cleaning methods.

The principal adverse impact from DPF application has been those instances in which the DPF prematurely plugged and in some cases suffered a failure because the system failed to regenerate or clean the filter properly. The principal cause of filter plugging was the failure to reach the exhaust temperatures needed to help initiate proper filter regeneration. The build-up of PM on the filter causes the engine backpressure to increase to a point where engine performance is adversely affected (e.g., loss of power) or the vehicle must be taken out of service to remove, clean (or replace) and reinstall the filter.

Reports in the literature generally agree that passive catalyst-based DPFs have either no measurable or only a slight impact on fuel economy. Often the difference reported is not statistically significant. DPFs using fuel combustion as a regeneration strategy will impact fuel economy. One study reported that a DPF using a fuel burner regeneration strategy had a fuel economy penalty of less than 2%. Catalyst-based DPFs do require the use of ULSD. Diesel fuel with less than 15 ppm sulfur has a lower energy content than conventional diesel fuel that translates into a slight fuel economy penalty (See "Ultra-Low Sulfur Diesel Fuel", below).

TECHNOLOGY DESCRIPTION

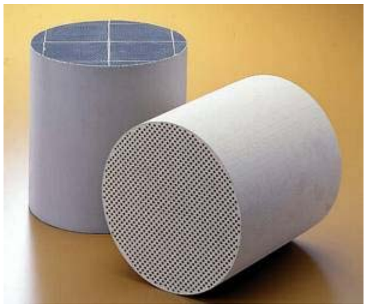
The DPF system consists of a filter encased in a stainless steel canister that is positioned in the exhaust stream and is designed to collect particulate emissions while allowing the exhaust gases to pass through the system as shown in Figure 3-1. A DPF system has three main components: 1) the filter that collects or "traps" the PM, 2) a means for removing the PM from the filter or a "filter regeneration strategy" and 3) a mechanism for determining whether engine back pressure is increasing due to the build-up of ash and other constituents on the filter surfaces. These three components are discussed below.

Figure 3-1, Typical Muffler-Replacement DPF Construction

Courtesy of Fleeguard

A number of filter materials have been used in diesel particulate filters, including ceramic and silicon carbide materials, fiber wound cartridges, knitted silica fiber coils, wire mesh, and sintered metals. Filter materials can be designed for varying levels of PM control ranging from less than 60% to greater than 90%. Currently, the most prevalently used filter materials in both OE and retrofit applications are ceramic cordierite and silicon carbide. An illustration of a ceramic wall-flow monolith is shown in Figure 3-2.

Figure 3-2, Example of Ceramic Wall-Flow Monolith



Courtesy of NGK

Since the volume of PM generated by a diesel engine is sufficient to fill up and plug a reasonably sized filter in a relatively short time, some means of disposing the collected PM must be provided. The most promising means of disposal is to burn or "oxidize" the PM in the filter, thus regenerating or cleansing the filter. Since the diesel engine-out exhaust temperatures are not always sufficient to burn the PM, a strategy to generate sufficient temperatures is typically needed. Achieving the temperatures needed for regeneration can be attained in a variety of ways, including:

- ***Catalyst-based regeneration using a catalyst applied on the filter surface*** – A base or precious metal coating applied on the filter surface reduces the ignition temperature necessary to oxidize the accumulated PM.
- ***Catalyst-based regeneration using an upstream oxidation catalyst*** – An oxidation catalyst is placed upstream of the filter to facilitate oxidation of nitric oxide (NO) to nitrogen dioxide (NO_2). The nitrogen dioxide adsorbs on the collected particulate substantially reducing the temperature required to regenerate the filter. This strategy has been employed in combination with both an uncatalyzed and catalyzed filter.
- ***Fuel-borne catalysts*** – Precious and base metal additives are added to the fuel to reduce the temperature required to regenerate the filter.
- ***Air-intake throttling*** – Throttling the air intake to one or more of the engine cylinders can increase the exhaust temperature and facilitate filter regeneration.
- ***Post top-dead-center (TDC) fuel injection*** – Injecting small amounts of fuel in the cylinders of a diesel engine after the pistons have reached TDC introduces a small amount of unburned fuel in the engine's exhaust gases. This unburned fuel can then be oxidized in the DPF to combust accumulated PM.
- ***On-board fuel burners or electrical heaters*** – Fuel burners or electrical heaters upstream of the filter can provide sufficient exhaust temperatures to ignite accumulated PM and regenerate the filter. In some cases the fuel is injected over a DOC.
- ***Off-board electrical heaters*** – Off-board filter regeneration stations combust trapped PM by blowing hot air through the filter system. This filter regeneration technique can be

performed with the filter still installed on the vehicle/equipment or by removing the filter and connecting it to the cleaning station.

A backpressure monitor/alarm component is a critical part of a DPF system. If the DPF is not effectively destroying all of the PM collected on the filter during normal engine operation, PM (ash and other constituents) will build up over time on the surfaces of the filter. If there is an engine problem (worn fuel injectors or turbocharger failure) that results in elevated levels of PM entering the filter, the PM build-up will occur far more rapidly. Increased levels of PM on the DPF filter surfaces will result in increased backpressure. If the backpressure level increases are high enough, it could result in a DPF failure and/or adverse impact on vehicle/equipment performance and fuel economy. If the backpressure monitoring system shows a sudden drop in engine backpressure, the cause may be a mechanical failure of the filter such as cracks or attrition. If the backpressure drops, the filter should be inspected.

A back pressure monitor/alarm system (see Figure 3-3 for example) tracks the backpressure levels, and warns the vehicle/equipment operator or technician that a problem exists before significant problems occur. It can also be used to help plan for and schedule filter cleaning. A variety of backpressure monitors exist using both audible and visual alarms to signal elevated backpressure levels. A popular alarm system employs a two-light (yellow/red) approach in which the yellow light is illuminated to signal that the backpressure has reach a level at which the DPF should be checked and cleaned as soon as possible and the red light is illuminated to signal that backpressure has reached a level that vehicle/equipment operation should cease. Some DPF systems are designed to have the engine’s electronic control system adjusted to allow the engine to allow the engine to operate in a low power mode when the red light is illuminated so that the vehicle operating in “limp mode” can return to the fleet yard. Alarm settings can be customized for each application.

Figure 3-3, Example of Back Pressure Monitor/Alarm System

Courtesy of MECA

Alarms are typically installed in view of the vehicle/equipment operator (typically on the dashboard) on the or in the engine compartment. The advantage of an alarm visible to the operator is that the operator can take corrective action immediately. The disadvantage is that if the light(s) illuminate due to an alarm system malfunction and not because of a real backpressure issue, the operator may be distracted or take action such as removing the vehicle/equipment from service when such action is unnecessary. When the alarm is placed in the engine component, it can be checked at the end of each shift by maintenance personal and if a light is illuminated, the backpressure and possible other causes (e.g., alarm sensor malfunction) for the illuminated light can checked.

Monitoring devices can range from a simple backpressure check to more sophisticated strategies that have a diagnostic and programming module that records not only backpressure, but information such as the history of control parameter settings, operating hours, and exhaust temperature as well. These systems not only alert the operator/technician to possible backpressure problems, but also provide data that can help identify the source of problems with either the DPF or engine components that can be addressed, subsequently.

Other types of DPF systems include:

Disposable Filters -- In select offroad applications, a disposable filter system has been used. The disposable filter is designed to collect the amount of PM that is likely to be generated during a working shift or two of operation while remaining within the engine manufacturer's backpressure specification. The filter is then removed and properly disposed.

Flow-through Filters -- A relatively new type of DPF system has emerged that does not trap the PM like the conventional DPFs discussed above, but instead is designed to provide exhaust flow turbulence and increased PM residence time. Several different design types are emerging, including wire mesh filter, pertubated path metal foil filter, and others. As discussed below, these flow-through filters have achieved PM reductions of 40% to more than 65%. While these levels are well below the PM control levels achieved by the conventional DPFs (over 90% PM reduction), they do have a broader application than the conventional DPF. This technology also has been referred to "high-efficiency DOCs", "partial flow DPFs", "DPFs", and "wire mesh DOCs". One flow-through filter design has been verified by CARB as a Level 2 technology that achieves at least a 50% reduction in PM and another combining a wire mesh filter plus a FBC has been verified by EPA as achieving over 55% PM reduction. Another concept is being tested on a transit bus in Michigan. This technology is composed of three elements: a wire mesh filter media, an air pulsation system and a soot reclamation/incineration system. The wire mesh media consists of layers of various compactness augmented with screens of various mesh size. This system agglomerates sub-micron and nano-size PM into dendrites (collections of tiny particles that resemble the shape of a tree or snow flake). As these dendrites grow in size, they break off and are collected on additional filter screens. The wire mesh media is then regenerated through pulsation of compressed air and the PM is collected in a bag.

B. Emission Reduction

DPF technology has demonstrated the capability to reduce total PM mass by 85% to over 90% in the exhaust of both on-road vehicles (e.g. transit buses, school buses, refuse trucks, line-haul trucks) and offroad equipment (e.g., construction, mining, and locomotives). DPFs have the capability of reducing total carbon-based particulates by over 99%, including the ultra-fine carbon particles. Flow-through filters have achieved PM reductions ranging 40% to more than 65%. DPFs employing a catalyst component (catalyst coating on filter, DOC in front of the DPF, or FBCs) can achieve up to a 90% reduction in HC (including toxic HCs such a PAHs, Nitro-PAHs, and benzene) and CO. DPFs also can be designed to reduce or eliminate diesel smoke and odor. The actual level of reductions measured will vary based on the type of DPF technology, the engine make and model, the operating cycle, the emission test cycle, and the testing equipment.

DPFs generally do not have an impact on total NOx emissions. One NOx-related issue has arisen with those DPFs designed to generate NO_2 in order to facilitate the oxidation of PM. Studies have found that this type of DPF system design can increase the NO_2 fraction of the total NOx emitted from the tailpipe. Studies have reported percentage increases of the NO_2 fraction of the total NOx emitted ranging from 6% to approximately 35%. The varying degree of increased NO_2 from these DPF systems may be attributable to specific design features, different type engines, mileage accumulation and other factors. Technology providers are making progress in developing strategies to minimize NO_2 production, including improvements in system design and catalyst formulations.

C. Status and Availability

Limited DPF retrofit demonstrations began in the 1980s, primarily on offroad applications such as mining equipment, and continued in the early 1990s, expanding to transit bus applications as well. In the late 1990s and early 2000s, the number of retrofit programs and vehicles/equipment retrofitted grew significantly. Today, well over 200,000 DPFs have been retrofitted on a growing variety of on-road vehicles and offroad equipment worldwide. In addition, a large number of new on-road vehicles have been and are scheduled to be equipped with DPFs as original equipment. The vast majority of the DPFs retrofitted on on-road vehicles have been catalyst-based passive filters, while offroad applications have included both active and passive systems. In new vehicle applications, DPF systems typically employ an engine-based active component combined in may cases with a catalyst-based strategy. Various flow-through filter designs have be introduced in retrofit applications for both on-road vehicles such as school and transit buses and offroad applications such as large construction cranes. The application of flow-through filters both as original equipment and in retrofit applications is expected to grow rapidly in the future.

STATUS OF DPFs INSTALLED AS ORIGINAL EQUIPMENT

Passenger Cars -- DPFs were introduced on new diesel passenger cars in Europe beginning in 2000 and today approximately 1,000,000 DPF-equipped automobiles have been sold. To date, no performance issues have been reported. Peugeot (PSA) was the first manufacturer to introduce a DPF-equipped passenger car and its system combined a FBC, a DOC in front of the filter, advanced engine controls and high pressure common rail fuel injection for filter regeneration. Over time, the amount of FBC was reduced which in turn extended the time between filter cleanings. At least six other passenger car manufacturers are selling DPF-equipped vehicles based on the PSA system with some systems using FBCs and others using catalyzed filters.

On-Road Heavy-Duty Engines -- A growing number of new transit buses are being sold with DPFs in Europe and the U.S. In the U.S., beginning with the 2007 model year all heavy-duty trucks and buses are expected to be equipped with DPFs to meet EPA's 2007 on-road HDE PM standard of 0.01 g/bhp-hr. These DPFs systems are expected to be integrated with advanced engine controls to insure filter regeneration under all operating conditions. DPFs are anticipated to be used to meet the more stringent standards being implemented in Japan beginning in 2005 and may be used in some instances to help meet HDE Euro 4 standards that also take effect this year.

Offroad Engines -- Over 20,000 DPFs have been installed on either new or existing offroad engines. OE applications have focused on mining and materials handling equipment. Beginning in 2011, DPFs are expected to be used on a growing number of offroad engines as EPA's Tier 4 Offroad Engine PM emissions standards are phased in over a multi-year period.

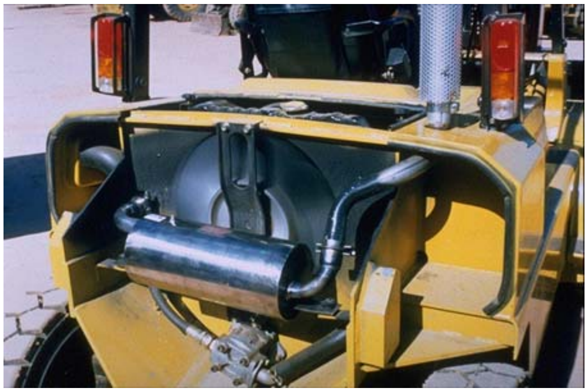
STATUS OF DPFs INSTALLED AS A RETROFIT TECHNOLOGY

Passenger Cars – Until recently, retrofitting diesel passenger cars with DPFs was virtually non-existent. Recently in Europe a flow-through filter concept using sintered metal foil became commercially available for selected passenger car models.

On-Road Heavy-Duty Engines -- As noted above, the vast majority of DPF retrofits have involved on-road vehicles. Vehicle applications include transit buses, school buses, freight and delivery trucks, refuse trucks, and utility vehicles such as dump trucks. Transit bus fleets in Sweden, Great Britain, France, the U.S. (including, California, New York, Washington State, and Washington, DC) and elsewhere have been retrofitted with DPFs. In the U.S. alone, over 80 individual fleets have retrofitted or are planning to retrofit vehicles or equipment with DPFs.

There are two very successful programs involving transit buses. The first is the Sweden Clean Cities Program (see Vol. I, Section 6) in which over 4,000 transit buses are equipped with DPFs with some buses accumulating over 250,000 miles of service without any significant issues. The New York City Transit Authority is the second program, in which over 500 transit buses have been retrofitted and up to 3,800 total buses are planned to be retrofitted with DPFs. Other examples of successful programs include the New York City Department of Sanitation in which several hundred refuse trucks have been retrofitted with DPFs and the ARCO/BP demonstration involving DPF retrofits on school buses, transit buses, delivery trucks and refuse trucks. Tokyo has instituted an extensive retrofit program. To date, tens of thousands of vehicles have been retrofitted with DPFs.

Offroad Engines -- DPFs have been installed on offroad equipment since 1986 with applications including mining and tunneling equipment, construction equipment, skid steer loaders, forklift trucks, locomotives, and other vehicles. Germany, Austria and Switzerland have established mandatory requirements for DPFs to be installed on mining and tunneling equipment. Switzerland has expanded that requirement to construction equipment and by the end of 2004, over 7,000 engines had been retrofitted with either active or passive DPF systems. DPFs in offroad applications typically have been used on engines rated at several hundred horsepower, but they are also used on smaller engines under 75 horsepower. Over 10,000 systems have been installed on forklift trucks, primarily in Europe since the early 1990s. DPFs have been installed on construction equipment such as wheel loaders, back-up generators, cranes (flow-through filter) and dump trucks. Since the mid-1990s in Europe, DPFs have been installed in very large engines, including over 100 locomotives on engines powered at up to 2,000 horsepower. Recently, a DPF was installed on a 4,000 horsepower diesel locomotive in Germany. Also, large stationary engines have been equipped in such places as California on engines in the range of 800 horsepower to 2,800 horsepower.



AVAILABILTY

DPFs are available from several manufacturers worldwide. All of the major catalyst suppliers have received EPA verification for their products for on-road applications, and at least one has now been verified for offroad use.

D. Selection and Use Criteria

As noted above, DPF technology is an application specific technology. This means that in some applications there may be factors that preclude a DPF technology from being used. In making a decision whether to use DPF technology in a particular engine application, the following criteria must be considered:

- The level of engine-out emission levels, including those from the engine lubricating oil.
- The engine operating exhaust temperature profile.
- Available space to equip the DPF.
- The level of sulfur in the diesel fuel.
- For certain catalyst-based DPFs, the proper NOx/PM ratio in the exhaust must be available.

For flow-through filters, the application criteria vary based on the level of the PM control efficiency. At the lower PM control efficiencies, this technology has a very wide application much like a DOC. At higher PM control efficiencies, the technology is applied on a case-by-case basis.

AVAILABLE SPACE

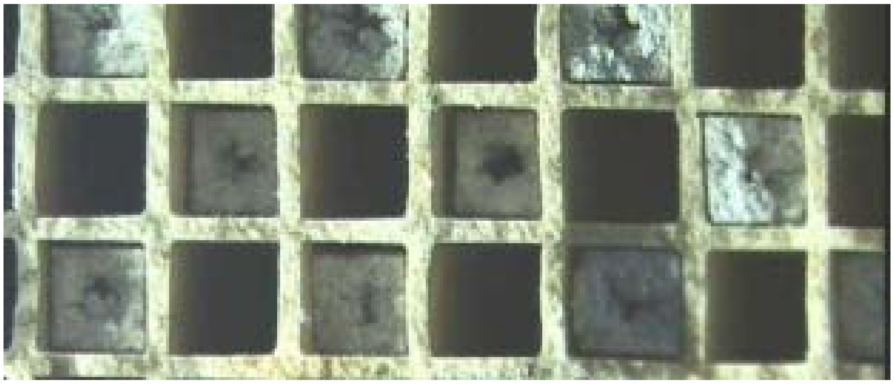
An important consideration in applying DPF technology is to ensure that adequate space is available on the vehicle/equipment to properly install the DPF. Making this determination involves several factors including that: 1) adequate space exists in the exhaust system to install the device at the appropriate place to provide optimum performance, 2) access exists to easily inspect and remove the DPF for cleaning, and 3) the DPF can be installed without adversely impacting the operation of the vehicle or impacting the safety of the operator.

Courtesy of MECA

Adequate space must exist in the exhaust system to properly locate the DPF. Since size of the DPF is often larger than the muffler it replaces, available space may be a limitation. Even if it is possible to fit the DPF somewhere else in the exhaust, the distance from the engine to the DPF may be too great that by the time the exhaust reaches the DPF, the exhaust temperatures are too low to sustain filter regeneration. Finding available space on some applications, such as older locomotives, has proven particularly challenging. If the only available suitable location for the DPF requires considerable time and effort to reach (e.g., the engine must be removed to allow access to the DPF), such an application may not be suitable for DPF application since the DPF filters must be removed and cleaned periodically. Finally, the location of the DPF should not interfere with vehicle/equipment operation (e.g., increased size of DPF should not interfere with vehicle/equipment clearance or create a safety risk to the operator, such as impairing the operator’s view). In most applications, available space, accessibility, and impact on vehicle/equipment operation or operator safety have not been a problem, but these factors still should be assessed when considering a DPF. In some cases, they may prevent the use of DPFs.

HIGH PM EMITTING VEHICLES/EQUIPMENT

If the level of engine-out PM emissions, including those from the engine lubricating oil are sufficiently high, the volume of PM reaching the DPF can overwhelm the ability of the DPF system to remove the PM collected in the filter before it accumulates and plugs the filter. High PM levels are a greater issue with passive DPF systems, but can be a factor in employing an active DPF system as well. High PM levels also can be an issue in applying higher efficiency flow-through filters. Therefore, older engines that were designed to meet emissions standards less stringent than those currently in place for both on-road and offroad engines and which often consume excessive lubricating oil are typically not good candidates for DPF applications. Two-stroke engines are a particularly challenging application for DPFs although DPFs have been applied to a limited degree on both on-road and offroad two-stroke engines.



In the U.S., passive DPF retrofits on trucks and buses have focused on 1994 and later model engines, with the significant majority of those engines being 2000 and later model year. For offroad applications, in which the use of active, external heat regeneration strategies can be employed, properly maintained engines dating back to the late 1980s have been retrofitted. Regardless of the age of the engine, it should be in proper working order, oil consumption should not be excessive, and worn engine parts such as fuel injectors should be replaced.

Flow-through filters have potentially broader applications than conventional passive DPFs, but exhaust temperatures and engine out PM levels should still be considered in applying FTFs.

EXTREMELY LOW EXHAUST TEMPERATURES

For those DPF systems, such as catalyst-based systems, the ability to properly destroy PM in the filter is influenced by the engine exhaust temperature and can only be employed if the minimum temperature for a given period is achieved (temperature/time requirement). If the operating exhaust temperatures are too low to enable the passive system to regenerate, PM will accumulate in the filter increasing backpressure, eventually adversely affecting engine performance, and causing potential DPF failure.

The minimum operating exhaust temperature requirement is typically expressed in terms of a specific minimum temperature (e.g. 250°C) for a specific percentage of the time the engine is operating (e.g. 40%) There is no one temperature/time minimum that can be applied to all passive DPFs systems for all applications. Rather, the required temperature/time minimum needed will vary based on the design of the DPF and the engine application. For example, a DPF system was recently verified by CARB as a Level 3 technology (minimum 85% PM reduction) for application on 1994 and later model year on-road engines when the exhaust temperature is at 210°C for at least 40% of the duty cycle. On the other hand, a study involving construction equipment found that DPF performance was poor when the equipment operated at exhaust temperatures in the range of 250°C. Over the past decade, DPF technology has shown continued improvement (e.g., improved catalyst formulations and filter designs) to expand the operating temperature window in which a passive DPF system will perform effectively. Flow-through filters also generally have a broader exhaust temperature operating window than conventional passive DPF systems. In each instance that a DPF technology is being considered, the technology manufacturer should be consulted to determine the minimum temperature/time needed for the engine application being considered.

In assessing whether a DPF is a potential option for a given engine application, a necessary step is to generate and record data (data logging) for the engine operating exhaust temperature profile over the expected duty cycle for that engine. In conducting the data logging procedures, two items are extremely important including: 1) where the temperature probe is placed in the exhaust, and 2) the operating cycle(s) on which the data logging is performed. First, the temperature probe should be installed in the exhaust as close as possible to the inlet of the DPF as possible. The data logging information will be less representative as the distance the probe is placed from the filter increases. If it is necessary to install the temperature probe a distance from the DPF, an adjustment to the data logging results should be made to account for the drop in exhaust temperature between the location of the temperature probe and the inlet of the exhaust. Second, data logging should include an assessment of the "worst-case operating scenario" in terms of low- or no-load operation, stop-and-go driving, time at idle, and when possible, the coldest ambient temperatures that likely to occur during the year.

Vehicles/equipment that operate at high-load for extended periods such as line-haul trucks or road graders are typically good candidates for DPF retrofits, while vehicles/equipment that operate with low loads and/or operate at idle for extended periods may not be suitable. A proper determination can be made for any application only if accurate and representative data logging is performed. For that reason, while fleet operators or others can perform data logging to preliminarily screen candidate vehicles/equipment, the technology provider should conduct its own data logging to confirm that its DPF technology is suitable for the engine application in question.

LEVEL OF SULFUR IN DIESEL FUEL

See F. Fuel Requirements below.

PROPER NOx/PM RATIO IN THE EXHAUST

For a catalyst-based DPF that uses the conversion of NO to NO2 to facilitate the catalytic regeneration of the filter, the proper ratio of NOx to PM in the engine-out exhaust is needed. When considering a catalyst-based DPF strategy, the product supplier should be consulted to determine that the NOx/PM ration of the candidate engine application is adequate to support the use a particular catalyst-based DPF design.

E. Installation and Vehicle Modifications

Application and use of DPF technology requires careful engine screening and preparation, regular checking of monitoring equipment, proper engine maintenance and periodic cleaning of the filter element.

PRE-INSTALLATION PROCEDURES

When selecting candidate vehicles/equipment for DPF retrofit, engines that burn excess lubricating oil, require frequent maintenance, or have a record of problems, should be rejected. Reviewing maintenance records and/or communicating with fleet managers and chief technicians will help identify vehicles that should not be included in the program. Also, as discussed above, in situations where a DPF relies on adequate exhaust temperatures to support filter regeneration, data logging of exhaust temperatures from the candidate vehicle/equipment applications over a “worst-case” operating cycle should be performed to determine if the exhaust temperatures are adequate to support filter regeneration.

Prior to installation, vehicles/equipment should be inspected (both the engine and the exhaust system) and any routine or necessary maintenance performed. This includes checking engine components and, replacing if necessary, such components as fuel injectors (worn injectors can leak fuel into the combustion chamber causing excess PM to collect on the filter) and the turbocharger (turbo-boost failure can lead to excess fuel being dumped into the filter which in turn can cause a catastrophic DPF failure) .

INSTALLATION AND VEHICLE MODIFICATIONS

The complexity of DPF installation can vary considerably. In some cases, installation is a relatively straightforward muffler replacement and in other cases, it is more complex because of such factors as limited space to locate the DPF and/or difficulty in accessing and working in the space where the DPF will be fitted. Also, the design of the inlet and outlet of the DPFs and connecting hardware will vary depending on the specific application. In some cases, modifications to the existing exhaust system will be needed. The time needed to perform a DPF installation can vary from as few as two hours to 10 or more hours, depending on the complexity of the installation. An important step in the installation process is for the technology provider to inspect and take measurements of the vehicles/equipment to be retrofitted. If a visual inspection by the technology provider is not possible, than at a minimum, drawing and other data sufficient to ensure proper DPF sizing and assembly design should be provided.

DPFs are often heavier and/or larger than the mufflers they replace. Therefore, care must be taken to insure that the installation hardware has sufficient strength to support the DPF. Failure to use the appropriate hardware can result in mechanical failure of clamps and brackets and can result in damage to the DPF. Special quick-release brackets are often utilized to facilitate quick removal of the filter for cleaning. Also, unless the exhaust temperatures are clearly sufficient with a large margin safety, insulation material should be installed on the exhaust system between the engine manifold and the inlet of the DPF to help maintain the exhaust temperature. In applications where the vehicle will operate in cold ambient temperatures, insulating the exhaust system is common.

Since DPF installations may be complex, installation is typically performed by the technology provider or its agent. In those instances where a large number of vehicles/equipment are being retrofitted and a highly professional maintenance staff exists, it may be cost effective, after consulting with the technology provider, to have fleet technicians trained by the technology provider to perform the DPF installations. In those cases in which fleet technicians perform the DPF installation, the technology provider or its agent should oversee the first few retrofits and subsequently at least spot check the installations of a sufficient number of additional retrofits to ensure adequate installation integrity. Finally, DPF installations should be carefully scheduled to minimize vehicle/equipment downtime. Adequate time for installation should be provided, including extra time for any unanticipated problems that may occur.

F. Fuel Requirements

DPF systems that do not employ catalyst based strategies and rely on external sources for filter regeneration generally have operated effectively on engines fueled with diesel fuel containing 500 ppm sulfur or, in limited cases high sulfur levels (e.g., underground mining equipment in Canada). Those passive and active DPF systems that employ catalyst-based strategies are adversely affected by the level of sulfur in the fuel.

Sulfur affects filter performance by inhibiting the performance of catalyst materials upstream of, or on, the filter. This phenomenon not only adversely affects the ability to reduce emissions, but it also adversely impacts the capability of these filters to regenerate; a direct trade-off exists between sulfur levels in the diesel fuel and the ability to regenerate the filter. Sulfur also competes with the catalytic reactions intended to reduce pollution and further creates PM through catalytic sulfate formation.

The vast majority of DPF retrofit projects in the U.S. and Europe use diesel fuel with sulfur levels less than 15 ppm. The use of this very low sulfur fuel enables filters to use catalytic formulations designed for maximum filter regeneration, for the highest levels of PM reductions, and for the least amount of sulfate generation. The use of diesel fuel with less than 15 ppm sulfur has been a key factor in the success of many program in terms of enhancing filter durability, performance and extended cleaning intervals. Several programs employing DPFs in the U.S. and elsewhere have used diesel fuels with sulfur levels greater than 15 ppm but less than 50 ppm. For example, U.S. projects involving long distance commuter buses, transit buses, and refuse trucks used diesel fuel with sulfur levels less than 30 ppm and reported no adverse impacts on DPF operating performance. DPF retrofit initiatives in Europe and in the U.S. on select on-road and offroad applications reported success with using fuels less than 50 ppm . One study did report that when a DPF system designed to operate on 10 ppm fuel switched to 50 ppm, a sharp increase in DPF failures occurred. As noted above, engines with catalyst-based DPFs operating on fuel sulfur levels above 15 ppm will have increased production of sulfate that adds to the overall PM levels.

Retrofit projects in the U.S. employing flow-through filters on such applications as school buses, transit buses and construction cranes are operating on conventional highway diesel fuel containing less than 500 ppm.

G. Maintenance

The principal maintenance item for DPFs is the periodic cleaning of the filter. Also periodic visual inspection of the: 1) DPF assembly hardware to insure the DPF is still firmly connected, 2) outer shell of the DPF for physical damage, and 3) exhaust system for leaks.

Under normal operating conditions, the filter collects the PM and periodically oxidizes the carbon-based PM. Inorganic material, such as phosphorus, sulfur, calcium, and zinc, derived from the lubricating oil, the sulfur in the fuel, and residue from engine wear will also be collected on the filter. These materials can form oxides and sulfate materials that remain on the filter. Over time, these materials accumulate on the filter and eventually will cause a pressure drop across the filter and cause the engine backpressure to increase. In addition, if the carbon-based PM is not completely combusted, it can also accumulate on the filter and contribute to backpressure increases. Finally, if a FBC is utilized, significant amounts of inorganic material will accumulate on the filter. To avoid backpressure increases above the engine manufacturer’s specification or to reduce backpressure build-up when it occurs, the filter must be cleaned periodically.

Filter cleaning should be performed in accordance with the technology manufacturer’s recommend maintenance schedule or when the backpressure monitor/alarm indicates engine backpressure levels approaching or exceeding the engine manufacturer’s specifications. Recommended cleaning intervals vary widely based on such factors as engine age, engine lubricating oil consumption, whether a FBC is used, vehicle/equipment application, and engine operating cycles. Recommended intervals are typically stated in terms of number of days/mile or hours of operation, which ever occurs first (e.g., annually or every 20,000 miles). In most applications, cleaning at least annually is recommended. Recommended mileage intervals for filter cleaning can range anywhere from 10,000 miles to 80,000 or more miles. For offroad applications, the recommended cleaning is stated in terms of operating rating hours.

In some instances, DPFs have continued to perform effectively well beyond the recommended cleaning interval. For example, the recommended cleaning interval is every 2,000 hours of operation for construction equipment in Switzerland. In a number of instances however, equipment operated well in excess of 2,000 hours without requiring cleaning. Similarly, several grocery delivery trucks operated over 300,000 miles over three and a half years with one truck requiring no filter cleanings and the remaining vehicles only requiring one cleaning over the three and half year period. Manufacturers of flow-through filters, given the nature of the filter design, do not typically specify recommended cleaning intervals. However, in some applications using the high PM control efficiency flow-through filters, annual cleaning is recommended. Also, if increased engine backpressure should occur, the filter should be cleaned in accordance with the manufacturer's recommended cleaning procedure. Several factors can extend the duration between cleaning intervals including: 1) reducing engine oil consumption through engine maintenance and, 2) using lubricating oil formulations with reduced ash forming properties such as low sulfur, zinc, or phosphorous levels. Also, DPF filter manufacturers have taken some steps to improve the ash storage capacity for a given size filter.

Several different types of filter cleaning methods can be employed. After removal from the vehicle/equipment, one popular method to clean the filter is using a combination of a pressurized air gun on one end to clean the filter and an industrial vacuum device at the other end to collect the ash. This approach typically takes less than an hour to complete per filter. Another cleaning method is filter heating/baking by placing the filter in an industrial oven or by using a stand-alone cleaning unit that includes a heating element to burn-off any organic soot remaining on the filter. This approach can take anywhere from eight to 12 hours. In some cases, both methods have been used. The DPF manufacturers will specify the types of cleaning that are appropriate for their DPF design and engine application. Some manufacturers offer automated or semi-automated machines or stand alone work stations for filter cleaning operations. These stations or machines can be designed to include pressurized air streams, vacuum collection, and/or heating capabilities. Fleet personnel can be trained to operate these cleaning devices. In addition, a growing number of organizations including the engine/vehicle OE dealers and distributors are offering cleaning services to fleets. The filter cleaning services include a number of service options including on-site cleaning and reinstallation of the filter at the customer's facility or "swap and clean" programs that substitute a clean filter element for the filter in need of cleaning.

Ash and other materials removed from the filter should be collected and disposed of in an environmentally appropriate manner. Workers and others should not be exposed to airborne ash; using a vacuum device with a sealed container to collect ash is one example of effective cleaning/collection technique. In some jurisdictions, DPF waste ash is considered to be a hazardous material while in others, it is treated as dry industrial waste. State and local environmental agencies are good sources for determining how DPF waste ash should be treated.

H. Costs

DPF technology costs can be broken down into hardware, installation, maintenance and operating costs. These costs can vary depending on a number of factors including the horsepower rating of the engine, the vehicle/equipment application and duty cycle and the volume of DPF units received under a given purchase order.

HARDWARE COSTS

In 2002, CARB provided an estimate of DPF hardware costs based on horsepower rating, as shown in Table 3-1.

Table 3-1, Estimated Costs of DPF Technology

Engine Horsepower	Hardware Cost
40	$3,300 - $5000
100	$5,000 - $7,000
275	$6,900 - $9,000
400	$10,500
1,400	$32,000 - $44,000

CARB also assumed an additional cost of $50 to $100 to cover installation hardware. CARB estimates seem to be reasonably in line with the reported costs of DPFs purchased in the U.S. over the past few years. For example, DPFs sold for use on on-road vehicle applications have generally fallen within the $5,000 to $10,000 range. The estimated costs of flow-through filters typically falls somewhere in the range between the cost of conventional DPFs and DOCs (e.g., approximately $3,000±). Information on the cost of DPF hardware for offroad applications is very limited, but the costs are expected to be comparable to, if not somewhat higher than, on-road applications of similar size and horsepower ratings. In some cases, depending on the degree of sophistication and capabilities, the backpressure monitoring system is sold separately. Monitoring systems can range from simple backpressure monitors to sophisticated recoding and diagnostic systems that monitor a number of different parameters including backpressure and exhaust temperature.

DPF manufacturers predict that as the technology is further optimized and the sales volumes of DPFs in both retrofit and OE applications increase, the hardware costs will be reduced. If this prediction is correct, then the favorable cost impacts of increased volume on price reduction should begin to appear in the 2006-2007 timeframe when the demand for DPFs will increase dramatically to satisfy EPA’s 0.01 g/bhp-hr PM standard for on-road engines.

INSTALLATION COSTS

The DPF installation is typically performed by the technology supplier or its distributor. The installation cost is sometimes included in the purchase price, but is often billed as a separate item. As discussed in “Installation and Vehicle Modification”, the time needed to install a retrofit can range from as little as two hours to over 10 hours. At an estimated rate of $65 per hour, retrofit installation costs would typically range from $130 to $650. These costs, however, could be substantially higher in situations in which complex or time consuming DPF installations are involved.

MAINTENANCE COSTS

The principal maintenance costs associated with DPF technology is the periodic cleaning of the filter. The actual cost will vary based on factors such as 1) the frequency of cleaning, any where from at the end of every shift to annually, 2) who performs the cleaning whether it be fleet personnel, the technology supplier or an independent third party, and 3) the type of cleaning method employed such as simply reversing the filter, using compressed air, or using a heat source. CARB has estimated that the annual maintenance costs range from $156 to $312 with labor of about two to four hours.

OPERATING COSTS

A concern sometimes expressed with utilizing DPFs is that it will adversely impact fuel consumption. However, as is discussed above, virtually all programs that have carefully evaluated the fuel consumption impact have found little or no fuel economy impact from utilizing a modern passive DPF. In those instances in which a fuel is used to facilitate regeneration, a slight fuel economy penalty can be expected. For example, one report noted a decrease in fuel economy of less than 2% for a fuel burner-assisted regeneration system.

For those DPFs systems requiring the use of ULSD, a slight fuel consumption penalty is possible from using ULSD due to the fuel’s lower energy content when compared to an engine operating on conventional on-road diesel fuel (less than 500 ppm). One report noted a 2%-3% penalty for delivery trucks, but other programs report only a modest or no measurable impact from using ULSD.