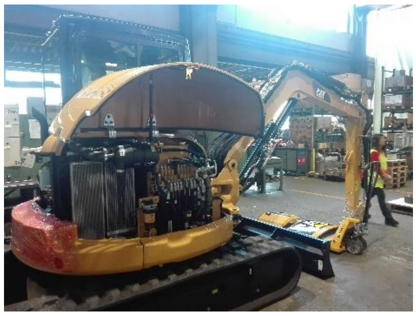
METHODOLOGICAL GUIDE

CALAC+
Programa Clima y Aire limpio
en Ciudades de América Latina

GOOD PRACTICE GUIDE ON THE USE OF DPF SYSTEMS IN NON-ROAD MOBILE MACHINERY



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Good practice guide on the use of DPF systems in non-road mobile machinery

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Cover photo:

TECSUP headquarters in Lima, Peru; AVESCO Langenthal Switzerland (below); Skid-steer loader on public roads in Lima, Peru (above)

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The Climate and Clean Air project in Latin American Cities Plus (CALAC+) pursues a vision of healthier cities that seek to reduce their emissions of pollutants and greenhouse gases (GHGs) by encouraging a shift to soot-free, low-carbon city buses and non-road mobile machinery.

This guide is part of a series of 7 technical documents developed by CALAC+ to promote knowledge and environmental management of machinery emissions reduction in Latin America. The topics covered include the generation of inventories, estimation of pollutants, emission control systems, regulatory standards policies and monitoring of measures adopted.

The *Good practice guide on the use of DPF systems in non-road mobile machinery* proposes a number of measures associated with emission aftertreatment of refitted or new engines with DPF (Diesel Particulate Filter) so as to ensure their emission reduction properties over the lifetime of construction machinery engines.

Content

1. INTRODUCTION

Health effects of diesel emissions

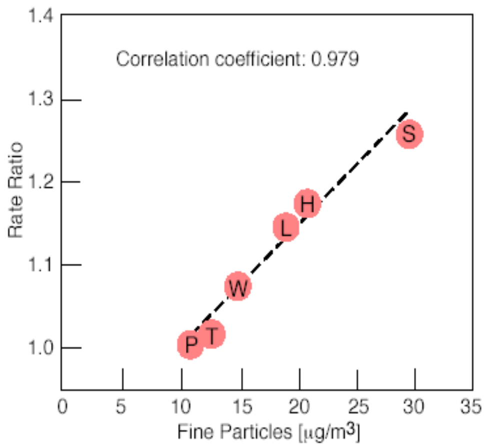
Today, virtually all construction machinery is powered by diesel engines, which are preferred to other alternatives for their energy efficiency, operation and endurance.

However, these engines emit very small particles that are harmful to health and have a high climate change impact. These are ultrafine diesel particles, which, due to their small size, comparable to that of viruses (around 100 nanometres), and their solid and insoluble condition, can enter the bloodstream through the lungs and subsequently be deposited in different parts of the body. They also carry other toxic substances, such as polycyclic aromatic hydrocarbons (PAHs).

The incidence of these particles in respiratory diseases, in various types of cancer and in heart attacks has been well documented by the scientific community, both in terms of toxicology (effects on the human body) and epidemiology (population health statistics).

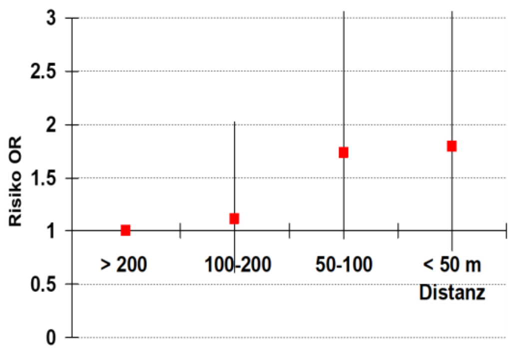
In terms of their impact on climate change, diesel particles consist of black carbon (soot), which is a greenhouse substance ranked number two, after CO_2, on the list of those responsible for global warming. Furthermore, since it is a short-lived greenhouse pollutant, its reduction has immediate climate effects.

Figure 1: Correlation between mortality and particle concentration.



Source: Dockery 1993

Figure 2: Risk of heart attack in relation to distance from home to road



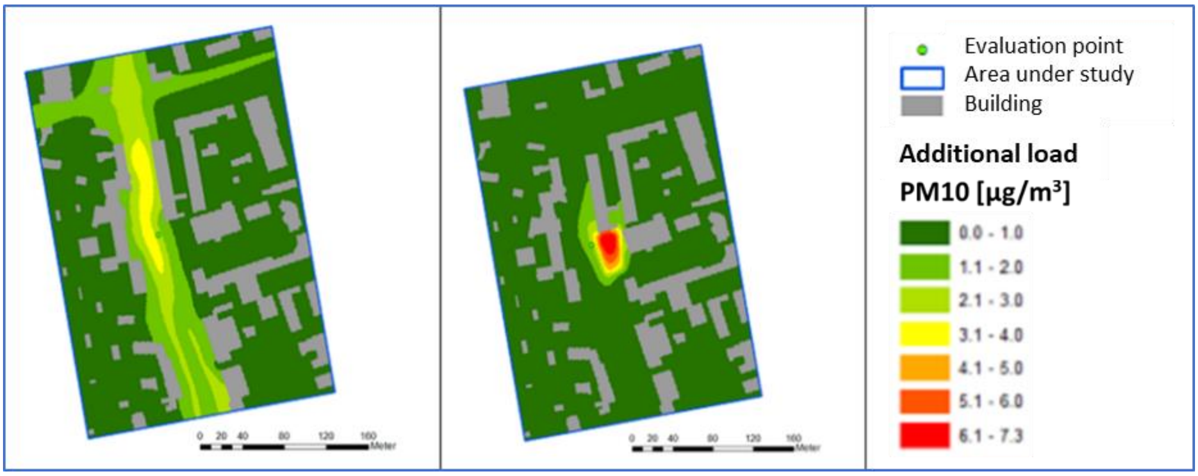
Source: Hoffmann 2006

Construction machinery and air pollution

The problem of particulate emissions from diesel engines is particularly critical in urban construction machinery because emission legislation for off-road machinery generally lags behind other similar sources such as on-road engines, mainly in emerging countries.

An example of this is the result obtained by a calculation model carried out by the IFEU Institute (Institut für Energie und Umweltforschung), with five Stage II standard construction machines operating during a year from 08:00 to 16:00 hrs., delivering a load of particulate material into the air, responsible for the increase of between 6 and 7 [ug/m^3], versus the contribution of the surrounding traffic with 46,500 per day, which represents an increase in concentrations of between 3 and 4 [µg/m^3][1].

Figure 3: Annual average value of local additional PM_{10} load of exhaust gas caused by traffic (left) and a sample construction site (right) for the area under study.



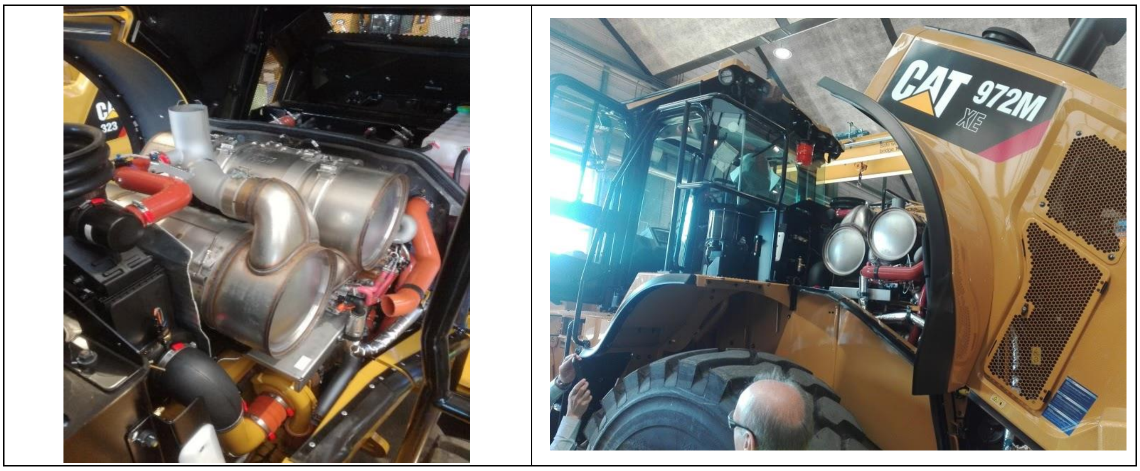
Source: [UBA 2014]

The solution

As a result of this serious problem, the European environmental authorities have moved towards the implementation of more rigorous standards, by incorporating the Stage V standard, which requires compliance with a maximum limit for ultrafine particle emissions. These are regulated by the particulate number (PN) limit per unit of mechanical energy released by the engine (10^{12} part./kW-hr). This standard has led to the mandatory incorporation of DPF (Diesel Particulate Filter) systems into the engines of new construction machinery. The system allows the filtration of ultrafine particles by more than 99% and can be installed not only in Stage V engines, which incorporate it from the factory, but also in machinery in use (retrofitting). This should be considered since the average lifetime of these machines can reach 20 years, making the replacement of the fleet by the new Stage V engines extremely slow.

[1] The information in this paragraph comes from [BERLIN 2015]

Figure 4: Standard Caterpillar Stage V engine of a front loader with DPF and SCR emission control system.

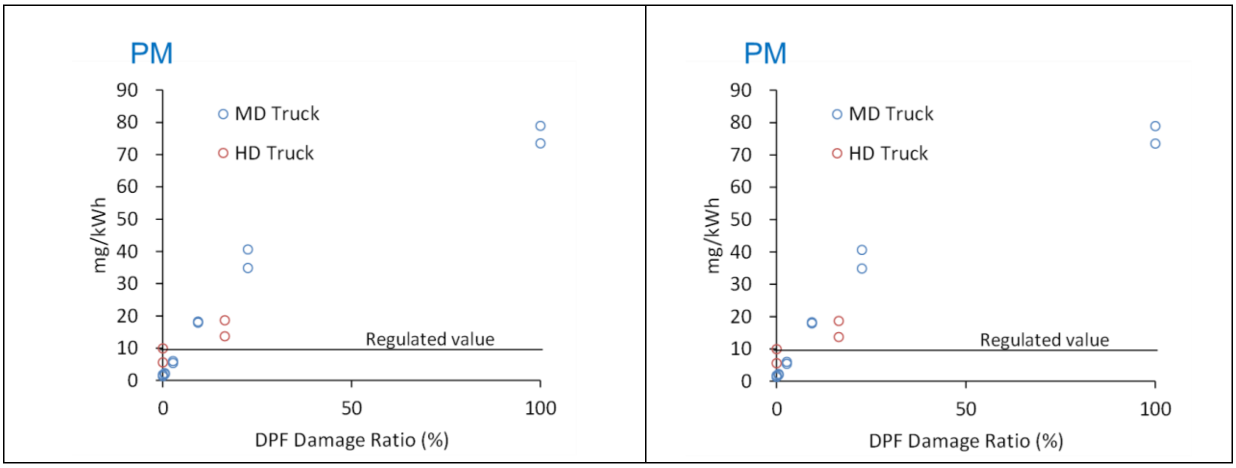


Source: View of AVESCO, Switzerland 2018.

However, the incorporation of DPF as an emission aftertreatment system has made the emissions from retrofitted or new engines with DPF very sensitive to the condition of these aftertreatment systems, with a high impact on vehicle emissions. As a result, failure of a diesel engine aftertreatment system can increase emissions by 2-3 orders of magnitude.

A study by Yamada et al (NTSEL-2015) showed that with 0.5% damage to the surface of the DPF, the emissions from a Euro VI engine can exceed the Particle Number (PN) emission limit. With 100% damage to the DPF the emissions exceeded the PN limit by 40,000 times. Because of the high impact caused by the failure of these aftertreatment systems, good maintenance and control practices are a priority.

Figure 5: Emissions in terms of the damage ratio in a DPF



Source: Yamada et al (NTSEL-2015)

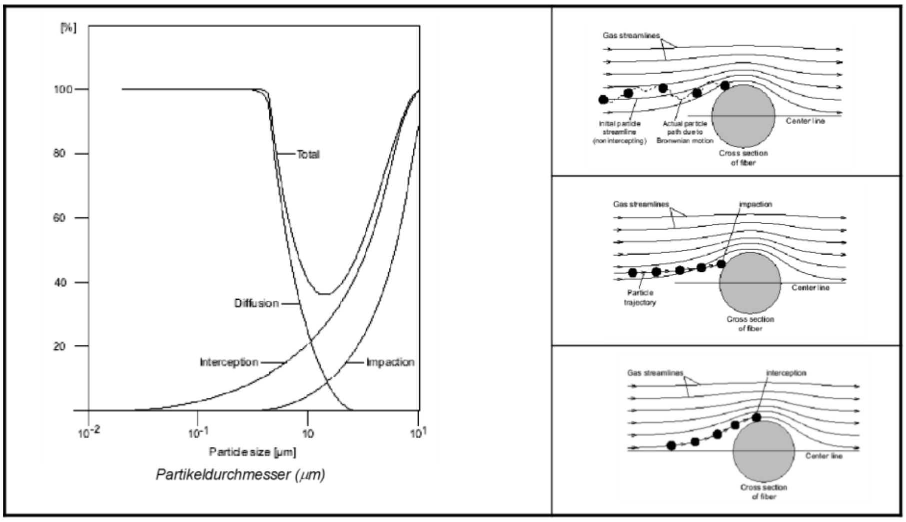
2. THE DPF TECHNOLOGY

Diesel Particulate Filters (DPF) are devices that capture particles from diesel engines. This type of technology has proven to be the most effective for controlling diesel particles, both in terms of mass (reduces approximately 90% of the mass of particulate matter), and in particle number (reduces around 99% of the number of particles).

Filter element

DPFs retain the particulate material that travels in the exhaust gases by passing it through a filter element (porous substrate). Particle retention occurs through three mechanisms, which depend on the particle size: interception, diffusion and impaction. Interception refers to the contact of the larger size and mass particles in the flow, which due to their inertia follow a straight path within the porous substrate, impacting the walls of the substrate, when a change in the flow path occurs. Diffusion is defined as the impact of the smallest and lightest particles, affected by the Brownian motion in a direction perpendicular to the flow, so that it has a high probability of impacting laterally on the walls of the substrate. Finally, there are those particles that, carried by the gas streamlines, pass close enough to the walls of the substrate to make contact (impaction). In all cases of particle contact with the filter surface, surface tensions retain the particle on the filter walls.

Figure 6: Physical mechanisms of nanoparticle deposition on the filter media.

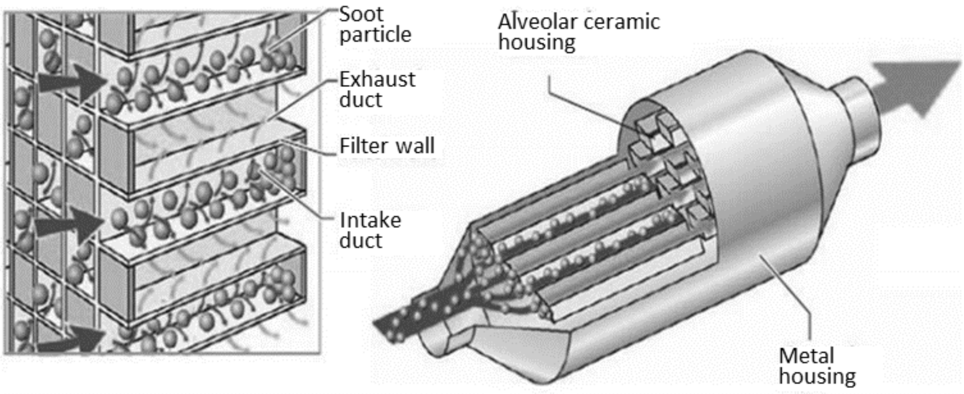


Source: TTM Mayer.

Since ultrafine particles are filtered mainly by diffusion, diesel filters need to optimize this mechanism by lowering the particle velocity and increasing the surface area of the filter element. This is a decisive factor when choosing a filter media whose porosity and size optimize this phenomenon. There are different types of filter media, such as cordierite, silicon carbide, sintered metal and even disposable paper filters.

In a closed filter all exhaust gases are forced through the walls. The clean gas can pass through the pores while the particulate material is trapped inside the filter. A diagram of a particulate filter and its basic operation is shown below.

Figure 7: Particulate filter operation.

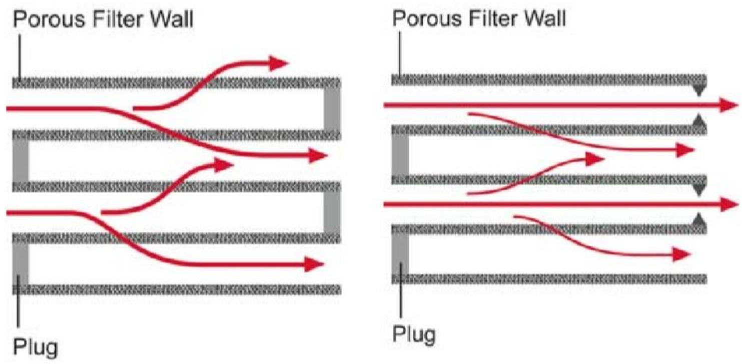


Source: Volks Wagen

For open filters, the fraction of gases passing through the porous substrate depends on at least two parameters: the engine operating conditions (torque and RPM) and the accumulation of particles and ashes obstructing the passage of gases through the substrate pores (substrate loading). Therefore, the fraction of filtered gases and the total efficiency of the open filter are higher as long as the substrate is kept clean and the exhaust gas speed is low enough. In practice, the efficiency of open filters deteriorates with use, dropping by 30%[2].

[2] SAE 2009-01-1087, Mayer et al.

Figure 8: Diagram of a closed filter ("full-flow filter") and an open filter ("partial flow filter")

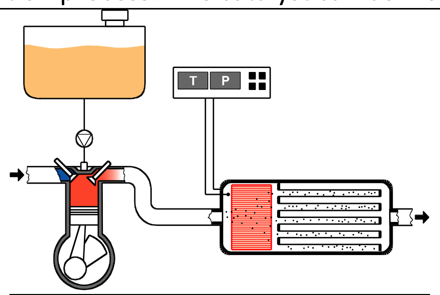


Regeneration

The filter element (porous substrate) is capable of storing a maximum amount of particulate matter in its volume, above which excessive clogging occurs when the exhaust gases pass through. This obstruction increases the backpressure to the engine. In order to keep the DPF working correctly, the particle load (soot) must be kept below the maximum values. This is achieved through the regeneration process, which is the combustion of the soot or carbon retained in the filter, and which is continuously carried out as part of the regular DPF operation. However, not all material retained in the filter element can be regenerated, as there is incombustible material, mainly ash from the lubricant, metal particles from abrasive wear in the engine and silicates from the intake air. This material must be removed from time to time by an external cleaning process.

A fundamental parameter for an adequate and permanent regeneration process is the temperature of the exhaust gases. Although in the exhaust gases of diesel engines there is generally a sufficient concentration of oxygen to burn off the soot retained in the filter element (regenerate), the temperature of these gases may be insufficient for this regeneration to occur spontaneously at an appropriate rate. Only at temperatures above 600 °C the regeneration rates are sufficient to prevent the accumulation of soot and the consequent increase in backpressure. Therefore, support strategies for regeneration are required, which are listed below.

1. **Passive Regeneration:** In the passive regeneration cycle soot particles are burned off (oxidized) continuously, using only the heat from the exhaust gases, and without external energy supply. This type of regeneration uses a catalyst that accelerates the oxidation process. This catalyst can be incorporated in one of the following ways:

	**CRT system:** By means of a diesel oxidation catalyst (DOC), incorporated just before the filter element, in the exhaust gas line. The catalyst accelerates the conversion of NO, present in the gases, to NO2. Soot

<table>
<tr>
<td>Figure 9: Schematic of the CRT system operation.
Source: TTM Mayer</td>
<td>oxidation is supported by the presence of NO2.</td>
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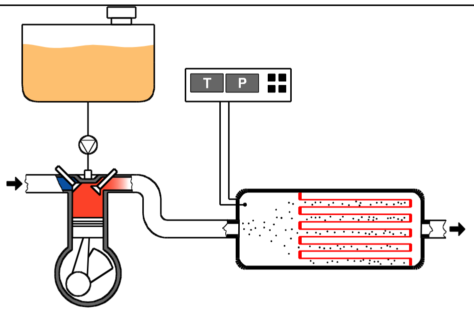
<td>

Figure 10: Schematic of the DPX system operation.
Source: TTM Mayer</td>
<td>DPX system: By means of a catalytic coating incorporated directly into the filter element. In this case the catalyst accelerates the soot oxidation by using directly the oxygen present in the gases.</td>
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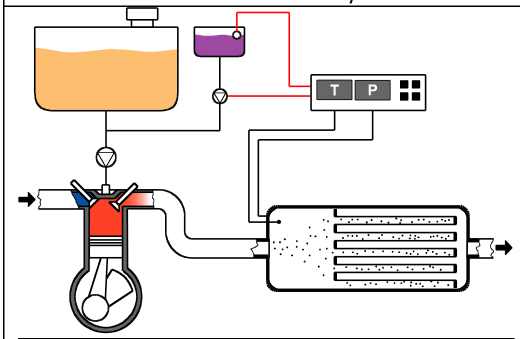
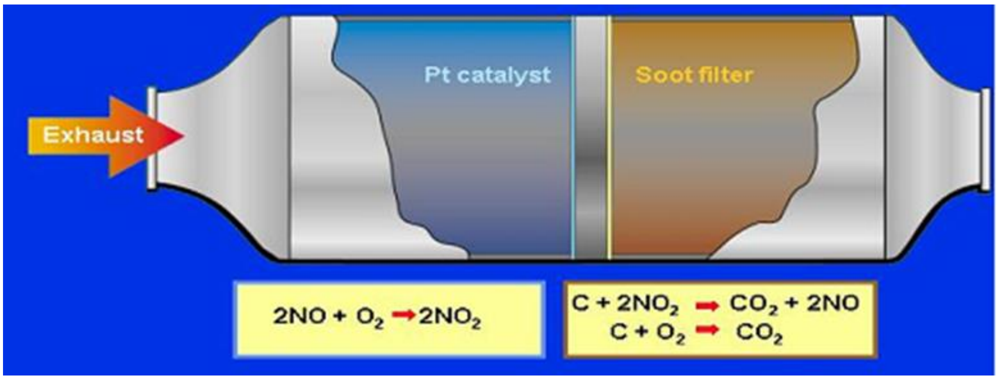
<td>

Figure 11: Schematic of the FBC system operation.
Source: TTM Mayer</td>
<td>FBC system: By incorporating the catalyst into the fuel by means of an auxiliary additive tank and a dosing element. The incorporated catalyst adheres to the particles facilitating soot oxidation.</td>
</tr>
</table>

A combination of the CRT and DPX system (a DOC and a catalytic coating of the filter element) is also possible. In all cases, the presence of the catalyst allows an adequate regeneration speed in the temperature range of the exhaust gases. In this process, the presence of oxygen and appropriate temperatures remain critical. These systems should also be considered sensitive to the presence of sulphur in the fuel, so the fuel quality should be considered. For example, for CRT systems, it is not recommended to have a sulphur content greater than 50 [ppm], which should be specified by the system manufacturer.

Figure 12: Functional diagram of a CRT system.



Source: Johnson Matthey

2. **Active Regeneration:** When engine operating temperatures or fuel quality are not suitable for a passive system, regeneration methods that allow additional energy supply or are less sensitive to sulphur are used. In general, these consist of a mechanism which activates regeneration according to the backpressure signal in the exhaust gases. There are different active regeneration systems, some of which are described below:

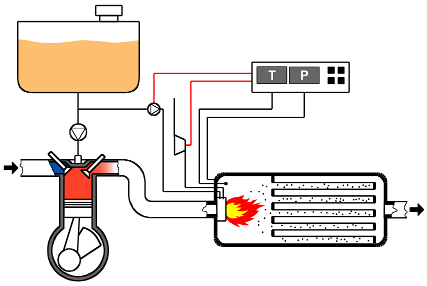


Figure 13: Schematic of regeneration with full-flow burner.

Source: TTM Mayer

Full-flow burner: Consists of a diesel burner placed just before the filter element. Exhaust gases can thus be heated above the soot combustion temperature (>600 °C), regardless of the operating conditions of the engine. The burner ignites according to the backpressure signal and goes out as soon as the filter is free of soot. The system is equipped with fuel and air supply devices and is electronically controlled according to backpressure signals and temperatures before and after the filter element.

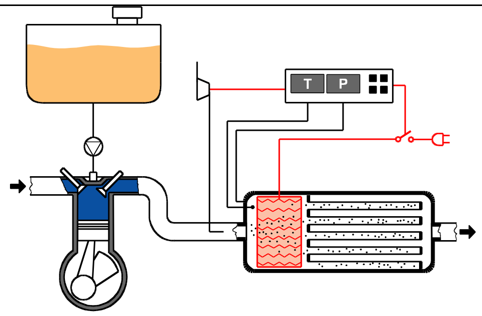


Figure 14: Schematic of on-board electrical regeneration.

Source: TTM Mayer

Figure 15: Schematic of on-board electrical regeneration combined with FBC.

Source: HJS

On-board electrical regeneration: Regeneration takes place while the machine is stopped, using an electrical connection to the power supply, which allows the exhaust gases to be heated at idle by an electrical heater or, if the engine needs to be stopped, by heating a flow of air supplied by a pump. This is a process that can take several hours and is carried out under highly controlled combustion conditions. In the case of metal filter elements ("sintered metal filter"), electrical regeneration systems can be used, combined with passive regeneration, which use the machine's own battery as a power source, requiring only minimal amounts of energy that allow the soot to be heated very locally, triggering the regeneration process.

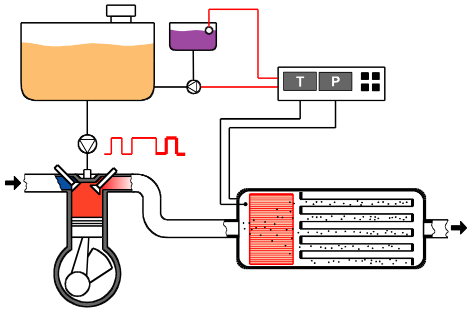


Figure 16: Schematic of post-injection regeneration in combination with FBC.

Source: TTM Mayer

Fuel post-injection regeneration: In this regeneration strategy the missing energy is incorporated by means of a small additional fuel injection that is burned off in the oxidation converter before the filter element, raising the temperature of the gases to the required level. This system works in combination with a CRT-type passive regeneration system.

3. **External regeneration:** When it is possible to remove the filter element frequently, for example daily in the case of small engines, or to replace the filter with a new one, an external regeneration method may be used. This requires the use of an external electric heater connected to the mains or an external burner, provided that it is a well-controlled process recommended by the manufacturer. Cleaning with pressurized water or compressed air is also possible. Once the regeneration is completed, the filter can be reused. In this case, a quick-release system is essential. Single-use disposable filters (such as oil filters) are also possible.

4. **High-altitude effects:** Although there are successful experiences in operating DPF systems in pilot studies carried out in Mexico City at 2,250 meters above sea level, and in the operation of Euro V buses with DPF in Bogotá, the engine mixture is enriched at high altitude as a result of reduced oxygen availability. This results on the one hand in a higher soot production in the engine, generating a higher demand for regeneration and filter volume, and on the other, a lower availability of oxygen in the exhaust gases, which is necessary for adequate soot combustion during the regeneration process. It is therefore recommended to first evaluate the performance of the technology in a pilot program.

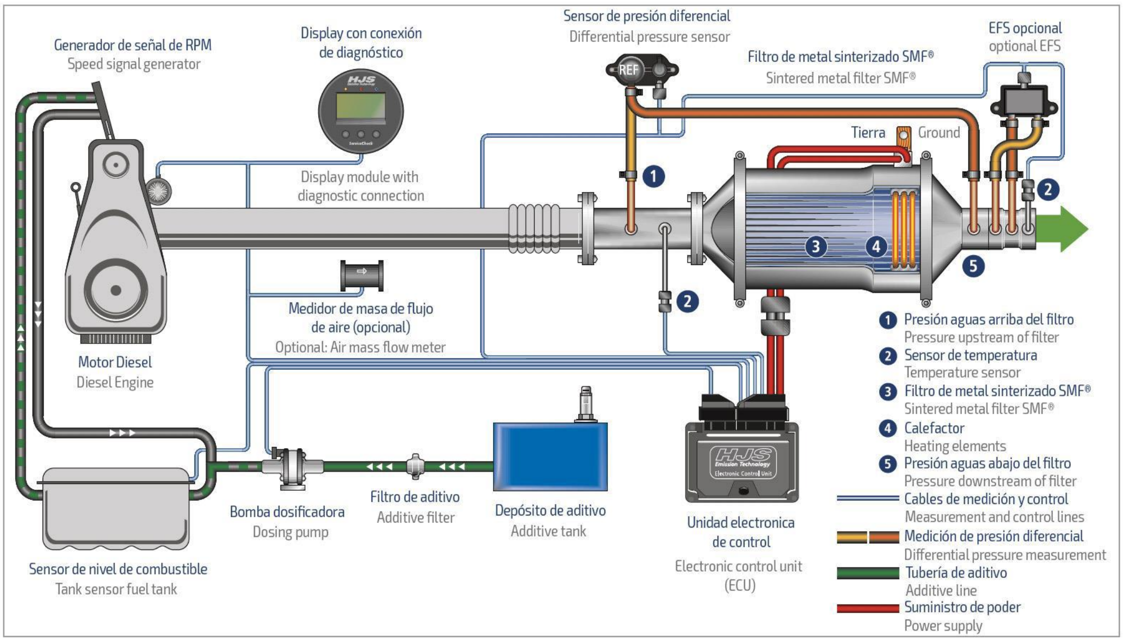
<u>Electronic control unit</u>

Since the DPF is a device installed in the tail pipe of the engine and can therefore cause clogging of the exhaust, the backpressure of the gases must be monitored before the filter. The permissible backpressure value is either that specified by the engine manufacturer or a value agreed with the DPF system vendor, according to technically justified recommendations. In any case, backpressures above 200 [mbar] are not recommended.

All DPF systems must be equipped with an electronic control device that monitors at least the backpressure before the filter and preferably the exhaust gas temperature, so that if the backpressure limit is exceeded, or the exhaust gas temperatures are not suitable, a clearly audible alarm (warning light) is triggered and the operator or maintenance personnel can verify the correct operation of the DPF and the engine. Usually the system has threshold values that trigger a pre-warning alarm that precedes the main alarm, so that there is time for maintenance staff to intervene. The unit leaves a historical record of the backpressure and temperature, as well as the events or alarms reported, during the last weeks of operation.

Notwithstanding the above, the DPF electronic control unit can be much more complex, depending on the regeneration system used, and can include the monitoring of other variables such as the FBC additive level, engine speed, engine temperature, intake air flow, etc. It may also have to act not only on the alarm ignition but also on the additive dosing pump, electric heater ignition, fuel post-injection, etc.

Figure 17: Schematic of components and operation of an HJS SMF-AR system monitor.



Source: HJS (https://www.dlsbv.nl/product/hjs-smf-ar-12/)

3. DPF RETROFIT

As mentioned above, with increasingly stringent emission standards for particulate matter (PM) and particle number (PN) for diesel engines in new machinery, DPF systems have become necessary. This is the case with the Stage V standard and also in some Tier 4 applications. However, it is also possible to achieve these emission levels in PM and PN in existing machinery with engines from previous standards. This requires retrofitting these engines with DPF systems equivalent in quality and efficiency to those used in new machinery. As a result, significant pollution reductions can be achieved, for example, in urban construction machinery fleets, long before they have to be replaced with new machinery.

Engine retrofit consists of installing a DPF device at the outlet of the exhaust gases, in order to filter the emissions, retaining the particulate material generated by the combustion in the engine. DPF retrofit requires special care and precautions to preserve the integrity and proper operation of the engine.

Figure 18: Caterpillar D8R bulldozer part of the Chilean Ministry of Public Works fleet, retrofitted with DPF.

Source: International Seminar: Soot-Free Construction Machinery, Santiago de Chile.

Engine operating conditions

In order to be successfully retrofitted, the engine must be in good maintenance condition, otherwise there is a risk of incorrect DPF operation and engine damage. Some basic requirements are as follows:

1. **Engine maintenance:** To ensure its operation, a prerequisite for DPF retrofit is to guarantee the correct condition and operation of the used engine, which must be maintained as per manufacturer's specifications. Therefore, prior to the filter installation, a diagnosis and maintenance of the following components is required:
   - Intake filter, change as per manufacturer's specifications
   - Oil filter, change as per manufacturer's specifications
   - Injection system, perform diagnostics and maintenance as per manufacturer's specifications
   - Turbocharger, perform diagnostics and maintenance as per manufacturer's specifications

- Cooling system, perform diagnostics and maintenance as per manufacturer's specifications
- Cylinder compression, diagnostics and maintenance as per manufacturer's specifications
- Valve set, perform diagnostics and maintenance as per manufacturer's specifications
- Check for leaks in the intake or exhaust system.
- Verify correct fixation to the exhaust system.
- Check pollutant emission values as per manufacturer's specifications.
- Check noise emission values as per manufacturer's specifications.

Before installing the particulate filter, all the above functions must be checked, except for new units. If the setting values differ from the manufacturer's specifications, the defective components must be correctly adjusted or replaced with new parts.

2. **Engine oil consumption:** Excessive oil residue in the exhaust gases can dramatically affect the DPF operation. The content of incombustible ash in these lubricants, which accumulates in the filter, accelerates the cleaning requirements by gradually blocking the passage of the exhaust gases. The high sulphur content of the lubricant also inhibits the filter regeneration process and deteriorates the catalytic coating in CRT systems. Finally, unburned traces of lubricant that reach and are deposited on the filter can generate high temperatures when burned during the regeneration process, fracturing the filter media. For this reason, the consumption of lubricating oil in the engine should not exceed the manufacturer's specifications, being in any case less than 0.5% of the fuel consumption. It is also important to check that there are no lubricant leaks from the turbocharger to the exhaust gases. Only Low-SAPS lubricants should be used in the engine (those with low sulphur and ash content).

3. **Exhaust gas opacity:** Exhaust gas turbidity is an indicator of engine damage that increases the emission of soot (black smoke) or burned lubricant in the exhaust gases (blue smoke). This should be measured with a partial flow opacimeter with a standard measuring chamber that has an equivalent length of 430 [mm]. Excessive soot in the gases, which exceeds the regeneration rate in the DPF system, will result in soot accumulation on the filter above the recommended design values (≤ 5 [gr/l]), and may cause DPF clogging or even a regeneration that damages the filter media.
The opacity values, before installation and during the use of the filter, should not exceed those recommended by the DPF system manufacturer or exceed the reference values given below:

Engine standard	Extinction coefficient [m-1] Maximum value
Stage II or lower	2
Stage IIIA or Stage IIIB	0,8
Stage IV	0,5

Source: Berlin 2015.

Figure 19: Different cases of off-road mobile machinery retrofitting

Source: TTM Mayer.

DPF System Certification

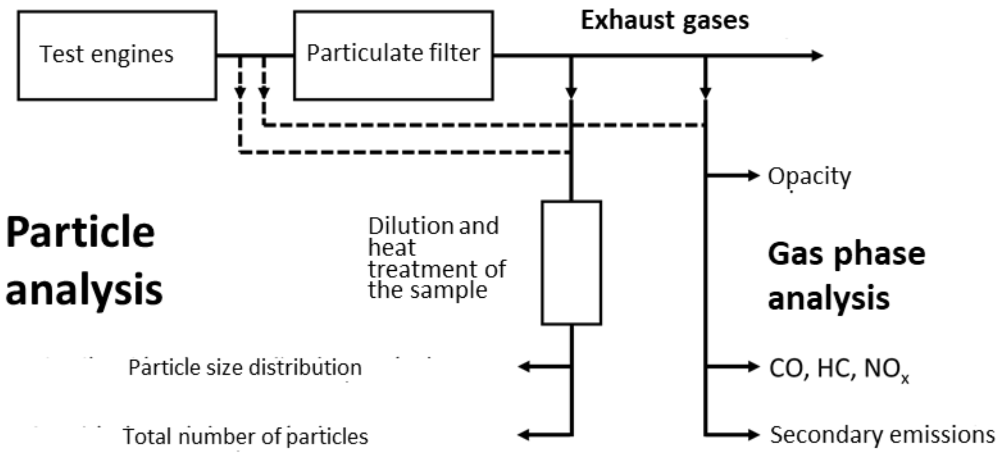
To ensure that the filter to be used in the retrofit meets the necessary quality and efficiency requirements, consideration should be given to certification of the DPF system. There are different public and private institutions, from different countries, that issue the certification of these systems (certifying body). They do so based on a set of tests carried out by laboratories recognized by these certifying bodies. The certifying body is ultimately responsible for issuing certification based on the results obtained in the tests. That is why it is very important to use systems certified by prestigious bodies and, as far as possible, to have local bodies in each country that give local recognition to these certifications (local approval). Such is the case of Chile, which has locally recognized the VERT[3], FOEN[4] and CARB Level 3[5] certifications in its legislation on this matter. In this case a local approval has been granted by the Ministry of Transport through the Vehicle Control and Certification Centre for specific retrofit applications, including some local tests in addition to the original certification.

The type of tests that should be covered in a certification are as follows:

- Laboratory test of the filter's retention efficiency, with minimum values in PN[6] or PM of 97% and 85% respectively. The efficiency during regeneration must be at least 80% in terms of PN.
- Laboratory test of secondary emissions. In order to avoid the formation of toxic substances as a result of the catalytic activity in the system, increases or presence of secondary emissions (NO2, PAH, dioxins, etc.) are verified.
- Field endurance tests. These tests are performed with the system installed in a real application, to examine the correct operation and efficiency of the system after a period of operation.

[3] It is a private association with offices in Switzerland dedicated to the promotion of the best technologies for emission control (https://www.vert-dpf.eu/). To access the list of certified systems, please visit https://www.vert-dpf.eu/j3/images/pdf/article/48/VERT-Filter-Liste-Sept-2017.pdf
[4] Swiss Federal Office for the Environment, which has a list of certified systems at https://www.bafu.admin.ch/bafu/en/home/topics/air/info-specialists/particle-filter-list/particle-filter-system-types.html.
[5] California Air Resources Board, which has a list of certified systems at https://www.arb.ca.gov/diesel/verdev/vt/cvt.htm
[6] For particle sizes between 20-300 nm

Figure 20: Schematic of test design for VERT certification.



Source: Rewritten from TTM Mayer.

DPF System Selection

As we have seen there is no single solution in the application of a DPF retrofit system and the filter must be adapted to the construction machinery and its operating conditions in order to optimize the operation and costs of the system.

The vendor´s experience is key, specifically that it has practical experience in retrofitting construction machinery with DPF systems.

The most important design criteria are the temperature profile of the machine, the available installation space and the size of the particulate filter. The size of the filter is designed in relation to the engine size and exhaust volume so that the maximum permissible exhaust backpressure specified by the engine manufacturer is observed. It is also necessary to consider the engine soot emissions when selecting the filter size since the higher opacity may require larger filters and ensure more frequent regenerations.

Since a higher exhaust gas temperature facilitates soot regeneration and then a greater number of regeneration methods will be available, it is recommended that the exhaust gas temperature of the equipment be determined over a period of a few weeks under all anticipated operating conditions (pre-datalogging). Based on these data, a suitable regeneration system can be selected.

Since seasonal effects (winter-summer) can slightly modify exhaust temperatures, it is recommended that the exhaust system and filter be thermally insulated and that the filter be installed out of reach of the engine fan airflow. This is particularly important when the pre-datalogging has been carried out in summer.

A general criterion for the selection of passive CRT, CCRT or DPX systems is the percentage of total time in which the gas temperatures are above 250 °C and must be greater than 50%, otherwise combined or active systems should be considered.

Another standard to be met for the selection of a passive CRT system is the mass ratio of NOx/Soot, which must be greater than 25 times. This is because in these systems sufficient NOx is required to produce the NO2 that is involved in soot oxidation. This parameter can be critical in engines with NOx control systems such as EGR or SCR, so it should be considered in the selection of the system as well as its location (it should generally be located before the SCR).

Figure 21: JCB Excavator data download in pre-datalogging process.

Source: Retrofit programme for the fleet of the Chilean Ministry of Public Works - University of Santiago - 2017

Installation, testing and approval

The purpose of this section is to specify the precautions and criteria to be taken into account as part of the installation procedure of the DPF system and the tests and records that should be considered in the installation process, in order to rule out failures caused by errors in the installation and to ensure proper operation of the system.

In the installation procedure the following steps should be considered:

- Checking the engine and the condition of the machinery.
- Replacement of the muffler by the DPF or other acceptable location.
- Verification of visibility and safety aspects.
- Functional test of the DPF and joint approval of the installation.

1. **Checking the engine and the condition of the machinery:**
   As stated above, the machinery to be retrofitted must be in good technical and maintenance condition. At the time of installation, evidence of good technical condition should be recorded on a form such as that proposed in Annex I. This form also indicates the tests to be carried out and the corresponding record.

2. **Replacement of the muffler by the DPF or other acceptable location:**
   In general, and if the dimensions of the muffler and DPF allow, the best location for the new DPF system is in the place of the muffler, inside the engine compartment. Therefore, one of the important conditions for verifying proper filter operation is noise measurement, as outlined in Appendix I.

3. **Verification of visibility and safety aspects:**
   In the case of installation of the filter in the engine compartment, since the temperature of the filter housing, product of the regeneration system, may be at a higher temperature than the original muffler, consideration must be given to the protection of components inside the engine compartment that may be flammable or have a low melting temperature (fuel lines, brake lines, hydraulic lines located in the vicinity of the filter, etc.). The type of insulation required must be determined by the DPF installer. For DPF installations outside the engine compartment, contact protection systems must be considered to prevent accidents.

   When installation is outside the engine compartment, rollover and falling-object protective structures must not be damaged during assembly, whether by perforation or welding. Nor must the passageway or emergency exits from the driver's cab provided by the manufacturer be obstructed. All connecting cables must be laid abrasion-free and protected against overheating.

   For safe operation, particulate filters shall be placed in such a manner that they do not obstruct the operator’s view from the driver’s seat. This objective can be achieved by placing the filter in the position of the muffler inside the engine compartment. If installation within the field of view cannot be avoided, safe us of the equipment must be ensured according to technical criteria. This can be ensured by the use of special mirrors or cameras. During work, visual aids must not be obstructed by moving parts of the machine.

   Regarding the field of view problem, reviewing the latest technical standard, such as ISO 5006 Earth-moving Machinery — Operator's field of view — Test method and performance criteria, is recommended.

Figure 22: Mirror or camera systems that help to solve visibility problems caused by DPF installation.

Source: [BERLIN 2015].

4. **DPF performance test and joint approval of the installation:**
Once the installation of the DPF is completed, proper operation must be tested. An ad-hoc form must be created to record the results of the tests and checks carried out as well as the approval of the installation by the machinery owner or his technical manager and the representative of the company responsible for the installation (see a proposed registration form in Annex I). The person responsible for the installation, if not the manufacturer of the DPF system himself, must have the appropriate authorization from the DPF manufacturer to carry out the installation. This is to ensure that the product warrantee is not voided.

The following is a list of tests and checks to be performed:

a. Identification of the machinery owner and the person responsible for the installation.
    i. Identification and contact details of the machinery owner.
    ii. Identification and contact details of the installation company.
    iii. Identification and contact details of the DPF system manufacturer.
b. Identification of installed components.
    i. DPF system code/model assigned by the manufacturer
    ii. Type of filter media (cordierite, silicon carbide, sintered metal, etc.)
    iii. Regeneration method (CRT, CCRT, DPX, FBC, diesel burner, electric burner, etc.).
    iv. Part number and serial number of installed components (filter element, catalyst, housing, supports, etc.)
    v. Manufacturer, part number and serial number of the monitor (datalogger) and additive dosing system.
c. Tests and checks.
    i. Opacity values at free acceleration before DPF and after DPF. The opacity before DPF should be within the range recommended by the DPF manufacturer (see Chapter 3.) Opacity after DPF must be less than 0.24 m-1.
    ii. PN values at low idle speed. The measurement of PM emissions after the DPF must be below 250,000 #/cm^3. An instrument complying with the Swiss standard SR 941.242 or equivalent for field measurement of solid particles must be used.
    iii. Exhaust noise values: The noise value must be recorded in dBA for fast response. The microphone should be located 0.5m away from the exhaust outlet and 45° from the line of the exhaust flow (See diagram in Annex 2). There must be no reflective surfaces such as walls, buildings or other vehicles within 3 meters. The noise values recorded with the DPF installed must be equal to or less than those recorded with the muffler.
    iv. Exhaust gas backpressure. Record backpressure values by means of an on-line monitor reading, for steady-state engine speed at idle and at maximum engine RPM. These backpressure values should be recorded with the original muffler and with DPF installed.
    v. Check for leaks in the intake or exhaust system.
    vi. Verify proper fixing to the exhaust system.
    vii. Check for oil, water, or other fluid leaks from the engine or chassis.

4. OPERATION AND MAINTENANCE

Regular inspection and maintenance of the filter and engine are necessary to ensure proper DPF system performance and emission stability. Preventive maintenance, as per the engine and filter manufacturer's instructions, is mandatory, particularly because the filter is sensitive to engine failure, and also because typical characteristics indicating engine failure, such as white smoke, blue smoke or excessive soot, cannot be detected after the filter installation, as the particulate filter eliminates these effects.

Periodic verification

Verify at regular intervals the leak tightness of the exhaust gas pipe, the suspension of the filter system, electrical connections and continuity of the pressure measuring line. Soot in the tail pipe indicates inadequate filtration.

Monitor or datalogger for operation control

The monitor or datalogger stores the data of the backpressure (and temperature if applicable), of the exhaust gases. If the limit is exceeded, the monitor issues an alarm. The analysis of the recorded data allows a detailed evaluation of the filtering system and helps to make decisions for corrective actions and preventive maintenance. The length of the records stored in its circular memory depends on the size of this memory and the activity of the machinery, but it should in any event be considered to store at least three months of operation.

The filter can affect the engine operation only through the backpressure generated on the exhaust gases, which may be slightly higher than the original backpressure of the engine before the DPF installation. Since this higher backpressure must be overcome by the engine, fuel consumption can be increased by up to 2% to 3%, but it does not impact the engine unless it exceeds the manufacturer's recommended limit or the maximum permissible 200 mbar for a prolonged period. The purpose of the monitor is to prevent this from happening by triggering warming light signals, which indicate the need for filter and/or engine service.

The alarms warn the driver acoustically and/or visually. In addition, these alarms are stored in the monitor's tamper-proof memory. The standard alarms are:

- Pre-alarm if backpressure exceeds 150 [mbar] (Yellow).
- Main alarm if backpressure exceeds 200 [mbar] (Red).
- Damaged filter if backpressure decreases rapidly.

Warning lamps and acoustic alarms must be strictly observed. Ignoring them can result in overheating of the system and damage to the filter and the engine. The monitor records all ignored alarms, generating information that can be used to invalidate the product warranty.

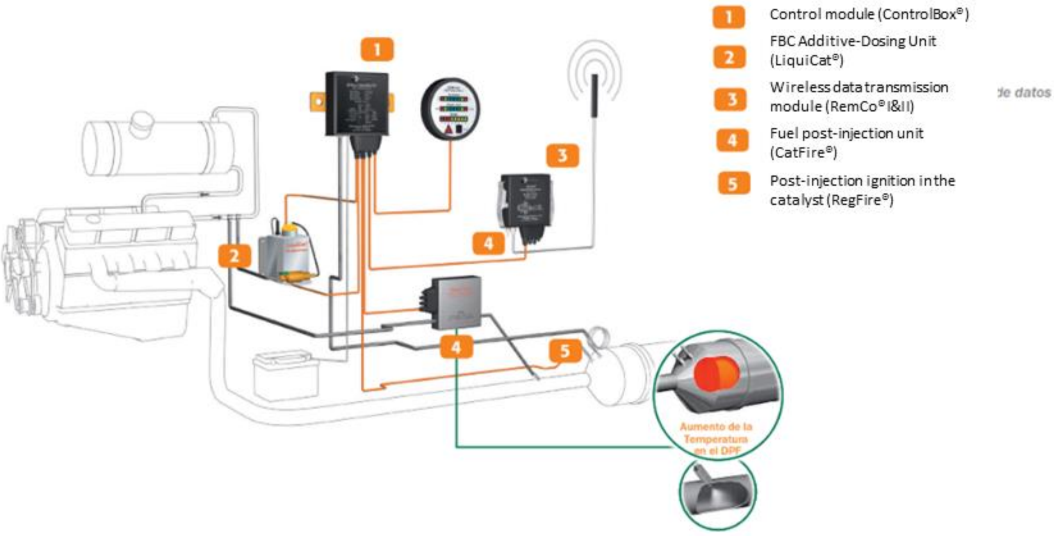
Today, monitors are available that allow data to be transmitted wirelessly, for example via GSM, to a central monitoring station. They can also transmit the alarms that are generated.

The backpressure may increase due to the accumulation of soot in the filter, which is the result of transient increases in particle emissions under a given load condition. However, these increases must be quickly overcome in the filter regeneration process. A different case is that of sustained soot accumulation, meaning either failure of the regeneration strategy or failure of the engine that has raised soot emissions above normal parameters.

One of the main risks of not observing the monitor's alarm signals is the excessive accumulation of soot on the filter, which can lead to uncontrolled regeneration, i.e. with a soot load above the filter's design conditions, which can cause harmful temperatures for the filter media and other system components.

In any case, a gradual increase in backpressure in the filter due to the accumulation of ashes from the lubricant and other incombustible substances such as metals due to abrasion or engine wear and tear and silicates from the intake air is normal. This is a gradual increase that occurs within 1,000 to 2,000 hours and is solved by cleaning the filter to remove the accumulated incombustible materials.

Figure 23: Set of devices and connections of a CPK monitor for different regeneration systems.



Source: Prepared by the authors from CPK diagram.

Lubricant and fuel quality

To reduce ash build-up, extend the time between cleanings and increase filter endurance, Low SAPS, low sulphur and low ash engine oils should be used.

Diesel fuel used in a diesel engine with a particulate filter must meet current low-sulphur fuel standards. The use of high-sulphur fuel (> 50 ppm) may void the particulate filter warranty. For higher sulphur contents, special sulphur-tolerant filter systems must be applied. Information about restrictions on the sulphur content of the fuel as indicated by the DPF system manufacturer is required.

Cleaning and ash removal from the filter

As indicated above, the filter should be periodically cleaned of ashes when the normal regeneration of the DPF system does not allow the backpressure to fall below 200 [mbar]. The usual cleaning interval is between 1,000 and 2,000 operating hours, when a low-ash engine lubricant is used. Metal filters can be manually cleaned with a hydro washing machine. This should be done on top of an oil separator and the suspended droplets should not be inhaled.

Ceramic filters shall not be cleaned with hot water, steam or compressed air and require a special cleaning machine. These generally use an oven to heat the filter element to 650 °C and burn off the soot. Subsequently the ash is blown out with a pulsating air jet. The air is fed at high speed into the channels of the filter matrix. The resulting pulse also acts on the end of the filter channel and loosens even the most resistant ash clogs. With this the cleaning efficiency can reach 99%.

Cleaning can be repeated 5-6 times during the lifetime of the filter. Ash is a toxic waste and must be disposed of in accordance with local regulations. To protect occupational health, cleaning of the filter should be done in a hermetically sealed machine.

When cleaning the filter, consider the DPF manufacturer's recommendations, as there are a large number of different filters with different properties and the filter vendor must specify the procedure for proper cleaning.

To avoid machine downtime during cleaning, a sufficient stock of replacement filters can be considered as part of maintenance planning, which can be used during this procedure. Maintenance management should consider the compatibility between the systems of different types of machinery and the associated cost of such stock.

Ashes and waste materials, depending on local legislation, belong to the category of hazardous waste and may require disposal by a licensed cleaning company.

There are service providers that offer full cleaning and disposal services. The contact person for this is the particulate filter vendor.

Figure 24: Components of a filter cleaning system

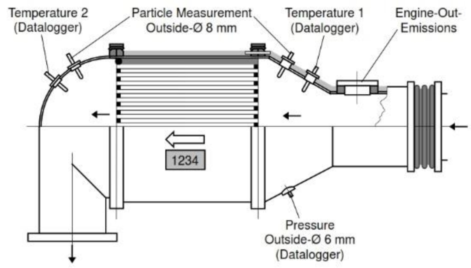
Source: Purexhaust S.A.

Exhaust gas verification

After the filter installation and every 500 hours, as part of the overall maintenance of the equipment, an exhaust gas measurement should be carried out for a proper diagnosis of the engine and filter condition and to provide reliable data for warranty purposes.

1. **PN measurement:** It is the best parameter to determine the efficiency condition of the filter. It should be measured at low idle using a certified PN instrument. To pass the test, PN ≤ 250,000 [#/cm^3] must be met. If PN is > 250,000 [#/cm^3], then a second measurement is recommended before the filter to determine the filter efficiency. The efficiency should be at least 95%. Damage to the filter may be the cause of the low efficiency. If less than 10% of the filter surface is damaged, it can be repaired in a specialised centre. Otherwise the filter must be replaced. The measured values must be recorded and compared with those measured in the installation acceptance tests.
2. **Opacity measurement:** This measurement is useful to know the condition of the engine so it should be measured before and after the filter. The measurement is performed under free acceleration with a certified partial flow opacimeter. The values before the filter must comply with the engine manufacturer's specification and with the values recommended by the filter manufacturer. Otherwise engine maintenance must be carried out. The opacity values after the filter must not exceed 0.24 [1/m].
3. **Measurement port before the filter:** The filter manufacturer should be required to have a measurement port in the filter housing inlet head (as shown in Figure 24), which allows access to the measurement probes of the opacity and PN instruments.

Figure 25: Right: Location of the sampling point before emissions pass through the DPF. Left: PN diesel emission measurement instrument for field work.



Source: TSI Manuals - TTM Mayer.

Typical failures and their causes

Below is a list of symptoms of failure, their causes and actions to be taken. These indications however do not replace the instructions of the engine and DPF manufacturer.

Symptom	Cause	Action
· Unexpectedly low backpressure alarm, as per manufacturer's values · Unexpectedly high backpressure alarm (as per manufacturer's values) which does not return to zero with the engine stopped.	· Backpressure or connection duct clogged or leaking. · Backpressure duct too narrow.	· Clean duct and connection. · Check for duct leaks and/or throttling · Install larger, sloped duct for runoff. · Install condensate trap.
	· Defective pressure sensor	· Change sensor.
· Visible black smoke emissions and high backpressure.	· Soot-overloaded filter.	· Produce regeneration at full engine load.
	· Regeneration failures.	· Readapt regeneration strategy to the operating conditions · Clean the filter in a cleaning furnace and compressed air.
· Visible black smoke emissions and low backpressure.	· Broken or damaged filter element	· Replace the filter element.
	· By-pass between the filter element and the housing	· Replace the filter element.
· Rapid increase in backpressure. Absence of regeneration.	· Very low exhaust gas temperatures in relation to historical values. · Engine with excess smoke.	· Change operating conditions of machinery. · Check thermal insulation of the DPF.

Symptom	Cause	Action
	· Turbocharger failure. · EGR valve failure	· Check engine and fuel injection system
· Backpressure increases irrespective of filter regeneration.	· Excess ash from the lubricant.	· Replace with Low SAPS lubricant and adjust the engine to burn off less oil.
	· Formation of plaster.	· Use low-sulphur fuels and lubricants (LowSAPS).
	· Ashes from the additive.	· Reduce the dosage or concentration of the additive
	· Fibers from the muffler.	· Relocate the DPF before the muffler.
	· Excessive engine abrasion.	· Repair the engine.
· Backpressure does not decrease after cleaning.	· Carbon in the pores of the filter element	· Burn off in furnace before cleaning.
	· Sticky deposits on the filter.	· Burn off in furnace before cleaning.
	· Sintered ash	· Replace the filter element.
· Unusually high temperature after filter according to historical values.	· Regeneration not controlled by excess soot	· Check backpressure alarms.
	· Regeneration too fast or not controlled.	· Check additive dosage.
		· Verify high HC emissions.
		· If the backpressure is correct then it is not a DPF problem
· Engine power decreases · Fuel consumption increases too much (>5%). · Coolant temperature rises too high.	· DPF backpressure	· Check backpressure
		· If backpressure is correct then it is not a DPF problem.
· Blue or light grey smoke.	· Excessive engine or turbocharger oil consumption	· Check engine.
· Soot deposits in the exhaust.	· Damage to the filter module.	· Measure PN or opacity at the exhaust outlet
· Visible acceleration smoke	· Too much fuel injection.	· Check injection at full load.
	· Delayed turbocharger.	· Check turbocharger.
	· Damage to the filter module	· Replace the filter element.
· Excessive smoke before DPF (opacity).	· Turbocharger damaged. · Full load limit. · Injectors	· Check turbocharger. · Check injection system.

<u>Training of construction machine operating personnel</u>

The owner of the retrofitted machinery must ensure that their maintenance technicians and operators are fully trained in the operation and maintenance of all the components of the system and know how to react to the monitor's warning light signals. This should be done by the particulate filter manufacturer or installer. Technical personnel should have documentation of this training as well as system operation and maintenance manuals.

Technical maintenance personnel and machinery fleet operators should also be trained in the good practices described in this document. The incorporation of a particulate filter in the exhaust system of construction machinery is a very important contribution to the health of the population and workers on construction sites but incorporating stricter maintenance protocols and good practices still remains a challenge.

5. ACRONYMS

CCRT	CRT with catalytic coating on the filter module (Catalysed CRT).
CRT	Continuously Regenerating Tramp.
DOC	Diesel Oxidation Catalyst.
DPF	Diesel Particulate Filter
DPX	Catalysed Particulate Filter (Trademark).
EGR	Exhaust Gas Recirculation
FBC	Fuel Borne Catalyst
NO2	Nitrogen Dioxide.
PAH	Polycyclic Aromatic Hydrocarbon
PM, PM_{10}	Particulate matter, 10 [µm] Particulate matter.
PN	Particle Number.

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ANNEX I

Particulate Filer	
Manufacturer (brand)	
Identification (part number, serial number)	
Type	
Certificate of conformity number	
Installation date	
Monitor/Datalogger	
Type	
Additive dosage system	
Type	
Vehicle/unit	
Category	
Manufacturer (brand)	
Type	
Year of manufacture	
VIN	
Engine	
Manufacturer (brand)	
Type	
Year of manufacture	
Power rating according to vehicle label	
Hours of service or kilometres at installation	
Filter acceptance measurement	
Opacity in K [1/m] at free acceleration	
Exhaust noise measurement at 45°/0.5 m at engine speed [1/min]	
Filter acceptance measurement	
Opacity in K [1/m] at free acceleration	
Exhaust noise measurement at 45°/0.5 m at engine speed [1/min]	
Filter backpressure at engine speed [1/min]	
Opacimeter	
Manufacturer (brand)	
Type	
Sonometer	
Manufacturer (brand)	
Type	
Inspection	
Inspection date	
Inspector	
Installer´s stamp/Date/Signature	

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