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November 25, 2002

VIA ELECTRONIC MAIL

Mr. Marvin W. Nichols, Director
Office of Standards, Regulations, and Variances
Mine Safety and Health Administration
1100 Wilson Boulevard
Arlington, VA 22209

RE: COMMENTS ON THE ADVANCED NOTICE OF PROPOSED RULEMAKING, DIESEL PARTICULATE MATTER EXPOSURE OF UNDERGROUND METAL AND NONMETAL MINERS.

Dear Mr. Nichols:

The Engine Manufacturers Association (EMA) submits the following comments in response to a notice in the Federal Register published on September 25, 2002 (FR 67: 60199-60203) regarding MSHA's intent to amend certain provisions of its existing rulemaking on diesel particulate matter concentrations in underground mines. Per the instructions given in the above notice, EMA is submitting our comments via electronic mail to comments@msha.gov.

EMA is the trade association representing the nation's leading manufacturers of diesel-fueled compression ignition engines that power much of today's mining equipment. As the manufacturers of the power source for such equipment, we understand the technical issues and options needed to reduce emissions and still maintain the performance and functionality of the mining equipment in question. Consequently, EMA provides comments on issues brought up in the ANPR that may affect the operation and performance of the equipment.

EMA stands ready to provide additional information or recommendations regarding these issues. Please feel free to contact me if you have any questions regarding these comments.

Sincerely,

Joseph L. Suchecki
Director, Public Affairs

AB29-COMM-16

UNITED STATES OF AMERICA
DEPARTMENT OF LABOR
MINE SAFETY AND HEALTH ADMINISTRATION

Diesel Particulate Matter Exposure Of	**)**
Underground Metal and Nonmetal Miners	**)**
Advanced Notice of Proposed Rulemaking	**)**

COMMENTS OF THE ENGINE MANUFACTURERS ASSOCIATION

On September 25, 2002, the Mine Safety and Health Administration (MSHA), published a notice in the federal register requesting preliminary comments regarding MSHA's intention to amend certain provisions of its existing health standard entitled "Diesel Particulate Matter Exposure (DPM) of Underground Metal and Nonmetal Miners" (Federal Register 67: 60199-60202). Specifically, MSHA requested comments and suggestions regarding proposed revisions to the standard.

The Engine Manufacturers Association (EMA) is the trade association representing manufacturers of internal combustion engines including diesel-fueled, compression ignition engines used in underground mining equipment. Consequently, while the proposed regulation does not set any direct standards or requirements on the products produced by EMA members, the actions that mine operators will need to take to achieve compliance with the proposed standard will necessarily affect the use, operation and performance of equipment powered by diesel-fueled engines. Consequently, EMA offers the following comments and recommendations regarding the technical aspects of controlling particulate emissions from diesel-powered equipment used in underground mines.

MSHA requested comments on nine areas of interest involving the standards, compliance plans and methodology, and technology to reduce diesel particulate concentrations in underground mines. EMA will limit its comments to two of these areas:

- Issue 1 Use of Elemental Carbon(EC) as a measure for diesel particulate matter, and
- Issue 8 Technological and economic feasibility

Issue 1 Use of Elemental Carbon as a measure for diesel particulate matter

In its original standard, MSHA established an interim limit of 400 micrograms per cubic meter of air and a final concentration limit of 160 micrograms per cubic meter of air as ambient standards for underground mines. MSHA established Total Carbon (TC) as the metric associated with these standards. MSHA is proposing to change the metric from TC to Elemental Carbon (EC) because of the belief that EC is a better measurement surrogate for diesel particulate matter (DPM) and EC can be more easily measured.

There is currently no accurate atmospheric marker for DPM. Diesel exhaust is composed of a complex mixture of constituents that are not unique to diesel combustion. Other sources of ambient particulate matter such as gasoline, fuel oil, coal, and biomass combustion produce many of the same constituents as does the combustion of diesel fuel. Consequently, it is very difficult, if not impossible, to determine accurate and reliable exposure estimates for DPM.

Nonetheless, EC often has been used as a marker or surrogate for DPM since EC was believed to comprise a large portion of total DPM and was not thought to be significantly emitted by other sources. Recent evidence demonstrated that EC is not an accurate marker for DPM in ambient air because 1) the relative proportion of EC to TC emissions from diesel engines has changed over time and 2) researchers are finding that EC is a larger component of emissions from other combustion sources. Accordingly, EC's usefulness as an exposure measurement for DPM in ambient air is questionable, and researchers are currently searching for new techniques and markers to measure DPM exposure.

Although there are significant questions regarding the use of EC as a diesel marker in ambient air where there are numerous combustion sources, EMA believes that EC may prove to be an appropriate surrogate for DPM in underground mining operations where the potential sources of EC are very limited. Because diesel sources may be one of the only sources of EC in underground mines, measurement of EC should be more reliably correlated with DPM emissions compared to ambient surface conditions.

In order to use EC as a compliance standard, EMA recommends that the following measures be taken into consideration.

MSHA should require the use of a single method to measure EC.

Two methods are commonly used to measure EC: the IMPROVE ECOC or Total Optical Reflectance Method and the NIOSH ECOC method. Because each method uses different temperature regimes during the analytical process, the two methods produce different measurements of EC. In general, although the two methods show excellent agreement for total carbon, the differences in peak temperature during the heating stage result in higher EC measurements by the IMPROVE method as compared to the NIOSH method.

DPM is not a single, unique substance in nature but is identified through regulatory definition and measurement methods. Because DPM is dependent on the methods used to measure it, there is no inherently "correct" concentration of DPM, i.e., use of either the IMPROVE or NIOSH method is acceptable. One simply cannot compare results obtained using the two methods. In order to obtain consistent and comparable results, especially for regulatory compliance purposes, a single EC measurement method must be specified.

MSHA should complete an emissions study of diesel mining equipment to determine the correct relationship between EC and total carbon in order to identify an appropriate EC compliance standard.

Although EC remains a significant portion of total diesel PM emissions, there is no consistent nor constant relationship between EC levels and DPM levels. Research has shown that the EC/TC ratio has changed considerably over time, is dependent on engine family and test cycle used, and varies with engine application. Consequently, there is no simple way to correctly relate EC measurement levels to the initially proposed TC standards from existing literature.

Assuming that MSHA wishes to maintain the currently proposed standard concentration of DPM in underground mines, a study should be completed to determine the appropriate EC/TC ratio. This study should include a PM characterization of the emissions from a representative sample of in-use diesel-powered equipment used in underground mines subject to the proposed rule. Emissions samples should be analyzed using the same sampling and analytical methods, and an EC/TC ratio specific to the mining equipment under study should be developed. Determination of the EC/TC ratio allows MSHA to then determine an appropriate EC standard that will be equivalent to the proposed TC standard and that can be used for compliance purposes.

Issue 8 – Technological and Economic Feasibility

In the Federal Register notice, MSHA requested information on the current technological and economic feasibility of control technology that can be used to reduce DPM levels in underground mines. There are a variety of control technologies that are available including such options as increasing ventilation rates, filtering cab air to reduce operator exposure, use of personal air filter devices, and reductions of DPM emissions through the use of appropriate control equipment on mining equipment. EMA comments will be limited to the use of control technology on diesel-fueled engines.

Emissions from diesel engines used in underground mining equipment are controlled by U.S. EPA regulations governing nonroad mobile sources. Currently, EPA has established PM standards for such equipment ranging from 0.75 to 0.15 grams per brake horsepower hour depending on the size of the engine. These nonroad PM standards are being phased in over a number of years. In addition, EPA is currently developing a new regulatory proposal to further reduce emissions from nonroad engines that is expected to be proposed in 2003. It is anticipated that EPA will require engine manufacturers to further reduce PM emissions, and PM emissions from new engines will continue to decline.

Because diesel engines are durable and reliable, diesel-powered equipment can last for many years, and it is common for a piece of equipment currently in use to have higher PM emissions rates compared to new engines because they were manufactured to older and less stringent emissions standards. Several options are available to reduce PM emissions from existing equipment including the purchase of new equipment that meets the latest emissions standards, use of cleaner-burning fuels, or equipping the existing equipment with devices to reduce emissions, commonly called retrofitting.

Retrofitting existing diesel equipment to reduce PM emissions is often viewed as a viable and preferred option to maximize DPM emission reductions. Such retrofits most commonly involve the addition of oxidation catalysts or catalyzed diesel particulate filters. However, it is important to recognize that retrofit technology for nonroad diesel engines is an emerging solution and that not all existing equipment can be successfully retrofitted. EMA provides the following comments on the status of diesel retrofit technology as it relates to nonroad and underground mining equipment.

The inherent variability in diesel-powered underground mining equipment operating requirements and duty cycle makes successful retrofitting difficult.

Diesel PM reduction technology is currently being applied to on-highway applications such as trucks and buses, and many assume that the same technology can be immediately applied to nonroad equipment. However, the duty cycle, engine operating parameters, and operating temperature for on-highway vehicles is much different than those for nonroad applications such as mining equipment. Engines in mining equipment must operate over a wider range of conditions and loads and also have a lower/more variable operating temperature. These characteristics make the successful application of retrofit equipment much more difficult.

Today's on-highway retrofit technology, such as catalyzed particulate filters, cannot simply be transferred for use in nonroad engines. The primary issues involve problems in the regeneration process due to low/variable engine operating temperatures, design and space configurations, excess vibration, operator visibility and safety concerns and availability of ultra-low sulfur diesel fuel necessary for the successful operation of the filters. For many nonroad engines, the most important concern is solving the regeneration problem to ensure that the filter and equipment perform adequately without the harmful build-up of soot and backpressure.

Currently, there is no available automatic PM filter system at a sufficient level of maturity and commercial viability for general application in all-underground mining equipment. Suitable PM filters must be developed that are applicable to the various equipment and operating conditions that are under consideration. Consequently, current control options are limited, and costs are relatively high. As the emissions standards are tightened for the entire nonroad engine market, DPM control technology will advance, specific technical solutions will be developed for the various applications, and controls will become more cost effective.

EMA has included a copy of a recent joint report with EUROMOT regarding the feasibility of PM filter applications for nonroad mobile machinery. Although the report was developed for the European market, much of the information is applicable to the current situation in the United States.

Mine operators must be given flexibility and sufficient time to allow DPM reduction technology to advance before it can be effectively applied on a large scale basis.

DPM filter technology needs additional time for development, testing, and verification before it can be cost-effectively and successfully applied to the wide range of equipment used in underground mining operations. The technical and economic considerations of applying DPM filters and retrofit technology to the diverse range of underground mining equipment must be taken into consideration as MSHA proposes revisions to the proposed standard. Given the current state of available control technology, it may be appropriate to extend the final compliance date to assure that technically sound, safe, and cost-effective retrofit equipment is available to meet the proposed standards. MSHA should not mandate the use of retrofit technology but establish reasonable interim ambient standards that take into consideration the viable options and time schedules available to mine operators to reduce DPM levels.

EMA recommends a flexible approach to regulation of DPM levels in underground mines that recognize the limited options currently available to mine operators.

Engine manufacturers and DPM filter manufacturers are working to develop solutions to reduce DPM emissions from nonroad engines and will continue to make improvements over the next several years. Although manufacturers have experienced success in reducing DPM from on-highway trucks and buses through the use of filter technology, the transfer of this technology to underground mining equipment has not been completed. Accordingly, DPM filter technology will not be available for all equipment for some time.

In the interim, mine operators should be encouraged to reduce DPM emissions through the introduction and use of low sulfur diesel fuel, retrofitting select equipment where a proven and verified oxidation catalyst or DPM filter is available, and the imposition of administrative and other controls that would reduce miners exposure to DPM. Any proposed standards and implementation schedule should be based upon realistic reductions of DPM emissions considering the current state of technology.

From: Suchecki, Joe [jsuchecki@enginemanufacturers.org]

Sent: Monday, November 25, 2002 4:33 PM

To: 'comments@msha.gov'

Subject: EMA Comments on ANPRM Regarding DPM Exposure of Underground Meta l and Nonmetal

TO: Comments@msha.gov

FROM: Joe Suchecki
Engine Manufacturers Association

DATE: November 25, 2002

RE: MSHA Request for Public Comments on DPM Exposure of Underground Metal and Nonmetal Miners

Attached are comments by the Engine Manufacturers Association regarding the above referenced matter.

<<MSHA1125.doc>> <<EMA Report.pdf>>

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Investigations into the Feasibility of PM Filters for Nonroad Mobile Machinery

A Joint EMA & EUROMOT Report

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AB29-COMM-16A

Investigation into the Feasibility of PM Filters for Nonroad Mobile Machinery

A Joint EMA & EUROMOT Report *)

31 August 2002

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*) EUROMOT The European Association of Internal Combustion Engine Manufacturers
EMA Engine Manufacturers Association

1. Executive Summary

Particulate Matter (PM) is generated as an inherent characteristic of the diffusion combustion process that occurs in diesel reciprocating internal combustion engines. Very significant reductions in PM emission from diesel engines have been achieved with advanced engine technologies. However, to reduce PM emission to negligible levels, some form of exhaust aftertreatment may be required.

This paper addresses the validity of the emissions reduction capability of PM Filter technology as a base assumption for determining future regulatory PM standards for Non-Road Mobile Machinery (NRMM) engines. The assessment considered primarily technical arguments but the commercial viability is also considered.

The investigation identified that NRMM applications present additional technical challenges compared to typical on-road truck use in respect to the functional requirements of the PM Filter system. These mainly relate to the regeneration process, but there are also significant other practical design issues as space, visibility and vibration limitations that need to be considered; these are discussed in the report.

The study concludes that for NRMM engines, a fully integrated engine and aftertreatment system is required with a regeneration system specification that is independent of machine application. Regeneration must occur regardless of machine duty cycle and without the need of intervention of the machine operator. This requires the development of active – automatic regeneration Filter systems. No such systems exist today at a sufficiently mature level of technological development required for commercial viability. It is anticipated that technological solutions will be developed. However, introducing PM Filter technology on NRMM will present a very significant challenge for industry in terms of the technological innovation but also considering the sheer volume of tasks associated with developing and calibrating engine/aftertreatment systems and integrating these into the vast range of non-road machine types.

While it is projected that PM Filter based emissions standards could be applied to NRMM within the next ten years, it is unreasonable to expect that such standards can be applied to all categories and types of NRMM within that timeframe. PM Filter systems will add significant additional cost and this will apply disproportionately to the smaller machines, potentially increasing equipment prices beyond market elasticity. Additionally there are practical constraints for some machine types and usage that introduce an impediment to the incorporation of PM Filter systems.

2. Conclusions

- The primary challenge in applying PM Filters to NRMM relates to Filter regeneration and requires a solution involving the integration of the aftertreatment system with the engine controls.
- Engine manufacturers have developed significant expertise and conducted considerable research activities on exhaust aftertreatment systems including PM Filters and, together with the knowledge of machine duty cycles and operation provided by equipment manufacturers, industry can provide an authoritative contribution to the discussion on the use of PM Filters for NRMM.
- Regulation forcing the use of PM Filters for NRMM diesel engines should not be considered for introduction before 2010, and consideration needs to be given to the different categories of engine and machine when developing an introduction schedule for regulated PM standards.
- PM Filter technology solutions for NRMM are required that provide active – automatic regeneration independent of machine application and duty cycle before it would be feasible to introduce an emissions standard for NRMM engine Type Approval predicated on the use of PM Filter emission reduction capability.
- Active – automatic PM Filter systems are not currently available at a sufficient level of developmental maturity and commercial viability for general application in NRMM.
- PM Filter technologies that are currently being applied in certain, very limited locations, pre-dominantly through retrofit, are not of the active – automotive type that would be required to support a general engine Type Approval requirement. This limited application of PM Filters on NRMM is not an indicator of the readiness of the technology as these are generally bespoke specifications designed for specific machines and modes of operation.
- The PM Filter technical solutions that are currently being developed for on-road truck applications to facilitate compliance with future emissions standards are not directly transferable to NRMM due to the narrower range of operation of such vehicles, providing a more conducive conditions for PM Filter regeneration.
- The PM Filter system that is currently offered on some of its products by a passenger car manufacturer is not suitable for NRMM due to system complexity, the need for fuel additives, and regeneration is not ensured regardless of duty cycle, thereby allowing Filter clogging under adverse conditions.
- A zero Sulphur mandate (<10ppm) for NRMM diesel fuel must be introduced and become effective before the introduction date of an engine emissions standard requiring the use of aftertreatment technology.

3. Recommendations

- Regulated PM standards for NRMM engines that are defined on the basis of PM Filter emissions reduction capability should not be introduced before 2010.
- Regulators should take into consideration the varying impact, both technical and economic, of applying PM Filters to the diverse range of NRMM products and define appropriate introductory schedules, derogation and flexibility provisions for the different engine and/or machine categories when considering future PM emission standards.
- Further studies should be initiated to determine the need to exempt particular NRMM products from, or defer the introduction of, PM Filter based emission standards, and to determine the basis of the classification, e.g. engine power category, machine application.

- A mandatory zero Sulphur (<10ppm) standard should to be introduced at least one year prior to the requirement to comply with an engine emissions standard based on the use of aftertreatment.

4. Scope

An assessment of the feasibility of applying the emissions reduction capability of PM Filters as a basis for defining PM emission standards for NRMM that could be introduced as a legislative requirement considering a 10 year timeframe.

5. Introduction

This report was compiled as a response to discussions regarding the possible future application of PM aftertreatment at an industry / regulator (EC, US EPA, EMA & Euromot) bilateral meeting during December 2001. Euromot and EMA agreed to study the issues associated with the application of this technology and produce a report for the regulators' consideration.

There appears to be a growing perception that PM Filter systems are proven technology, or will mature to achieve this status within a short time due to current research and development activities in this field. This perception is largely based on the recent limited introduction of catalytic regenerating Filter systems for Heavy Duty trucks and/or buses in certain regions driven by local regulation or incentives, as well as very limited, but well publicised, introduction by a passenger car manufacturer. Promulgated future PM emissions standards for HD trucks in both the US and EU are predicated on the use of PM aftertreatment systems. In addition, of course, PM Filters have been used in some off-road equipment niche sectors for some time.

The purpose of this report is to determine the validity of this perception in respect to the maturity of PM Filter technology relative to the requirements of non-road equipment, and to determine any constraints that may apply in regard to its application to the diverse range of non-road mobile equipment.

6. General Comments

The engine industry is committed to environmental responsibility and supports the judicial introduction of advanced emissions control technology for IC engines, through regulation of emission limit standards. Therefore, recognising the PM emissions reduction potential of PM aftertreatment technologies, the industry is eager to establish the opportunity for the future application of aftertreatment systems for NRMM engines together with other emerging emissions control technologies.

Non-road engine applications present additional challenges compared to on-road vehicles in respect to specifying PM Filters. A non-road engine is typically designed and manufactured for use in a range of different machines, each type with different typical duty cycles, and different duty cycles for individual machines of the same machine type depending on the job to which it is applied. The challenge is, therefore, to develop an integrated engine / aftertreatment system that has a specification which is independent of machine type and application. This specification must account for the diverse range of load cycles that engines of this type experience in the broad range of applications, including extended operation under light load operation, which is not untypical in the use of many machines.

Additionally, consideration must be given to aspects such as the more hostile environment in which non-road machines operate, and operator working conditions.

A definition of the functional requirements of a PM Filter system for NRMM application is needed to provide a criterion for determining the technical feasibility of technology options. One of the key functional requirements is that the PM aftertreatment system must be essentially transparent to the machine operator, i.e. an operator should not necessarily be even aware of the incorporation of a Filter in his machine.

The regulated introduction of PM Filters (through emissions standards) should not place an additional burden on the machine owner / operator other than the increased initial cost of a new machine, and this cost increase should be within the market price elasticity affecting machine replacement / rebuilt decisions. The incorporation of a PM exhaust aftertreatment system should not impair the functionality of a machine or reduce its utilisation potential. Systems which do not satisfy these criteria will be at risk of being defeated by machine owner / operators. It is probable that unreliable Filters prone to failure, Filters requiring off-board regeneration or regeneration support from external sources, or systems which require regular maintenance, would be removed by operators in the absence of regulatory inspection and maintenance activity.

The feasibility of incorporating PM Filter aftertreatment in non-road machines needs to be considered in terms of technical and economic feasibility for the different segments of engine / machine types within the broad spectrum of non-road equipment. A solution that may be satisfactory for a 400 kW machine may not be viable for a 40 kW machine.

7. Review of PM Filter Technologies

There are three basic elements to the operation of a PM Filter on a diesel engine. These are the collection of PM, oxidation of the collected carbon and the monitoring and control of these events. The technologies associated with these elements are considered.

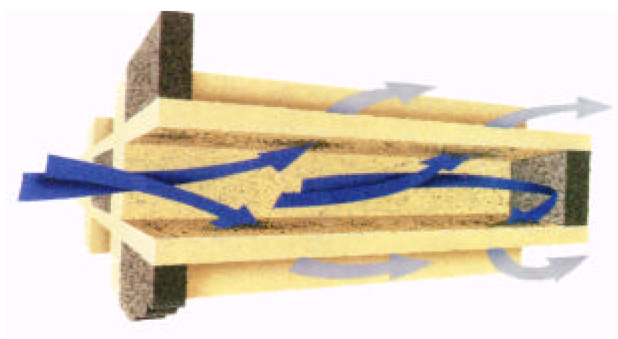
7.1 Collection of PM – Filtering the Exhaust Stream

All PM Filter systems are based on incorporating a Filter in the exhaust stream of an engine that prevents the passage of solid particles while presenting a porous medium for the flow of the exhaust gases. Of course, the operation of a Filter relies on a process for oxidising the collected material to ensure that the porosity of the Filter to the gases is not eliminated through blockage of the gas flow passages by accumulated PM. However, the most fundamental functional requirement of a PM Filter is that of collecting the PM with ash accumulation as a byproduct, and there are various Filter technologies, each with their specific advantages and disadvantages.

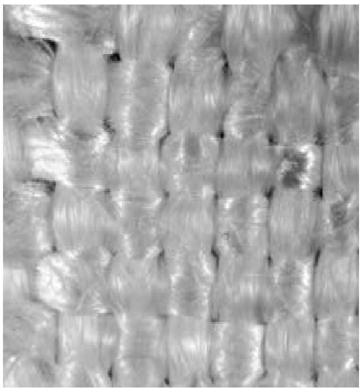
Filter Type	Filter Material	Description	Advantages	Disadvantages
Ceramic Monolith	Cordierite	Cellular structure of porous ceramic material, intake channels closed at the outlet side and outlet channels closed and the intake side, so that the exhaust is forced to flow through the porous walls and the particles are Filtered. Although the pore diameters are in the range of 10-20 micrometers, soot particles with an average diameter of 0.1 micrometer are Filtered with high effectiveness (main Filtering mechanism: diffusion of particles to the walls of the pores).	- Sufficient thermal stability with normal regeneration processes and soot loadings - Relatively low price	- Insufficient stability, when the Filters are overloaded with soot (melting of the ceramic material at temperatures exceeding 1200°C) - Brittleness of the material (cracks possible by high temperature gradients or by mechanical stress). Detailed know-how necessary for the canning of the Filter -
	SiC (Silicon Carbide)		- Higher thermal stability than Cordierite (risk of melting processes with uncontrolled soot burning lower, but still existing) - Higher mechanical stability than Cordierite, so that thinner walls and lower Filter volumes can be realized	Significantly higher price than Cordierite
Tissue of ceramic fibres			No sensitivity to mechanical stresses	May release soot at high back pressure, and expensive

Sinter metal Filters	High temperature resistant austenitic, porous sintered metal sheet	Manufactured by alternately welding two Filter sheets back to back at the inner circle, followed by a front to front at the outer shape to form a pocket, which enables wall flow filtration on large Filter areas. Mechanical properties are determined by the supporting wire mesh, porosity by the respective metal powder. Wire mesh and metal powder are metal-bonded during the sintering process. The gas flows from outside to inside of the Filter. Therefore, all Filtered particulates and ash are accumulated on the outer Filter surface, and are directly accessible from outside.	- May be widely adapted to canning design and space - High tolerance against soot overloading - High heat conductivity prevents local temperature peaks and thermal damage - Good ash accumulation performance enables a good long-term operation with respect to cleaning, backpressure and thermal stability - Suitable for all regeneration techniques	Higher cost than Cordierite ceramic monoliths
Ceramic or metallic foam			Less sensitivity to mechanical stress	Lower efficiency than monolith, expensive
Metal substrate block	Soldered corrugated steel foil		"Open" system, no backpressure increase	Sophisticated timing of regeneration due to flow dynamics

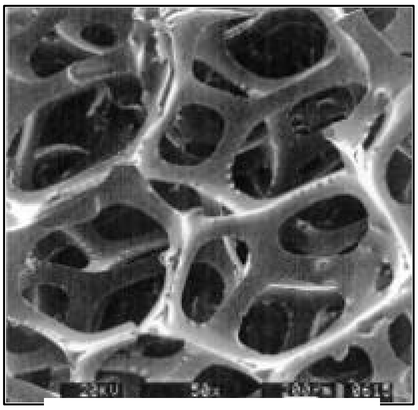
Fig. 1: Samples of Filter Substrates



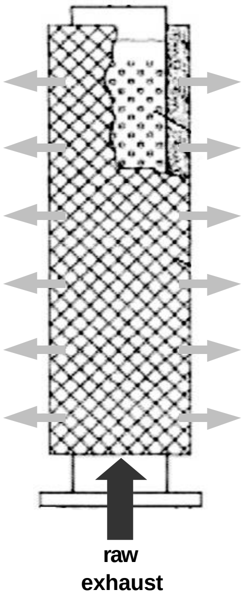
Wall-Flow Ceramic Monolith (Cordierite or Silicon Carbide)

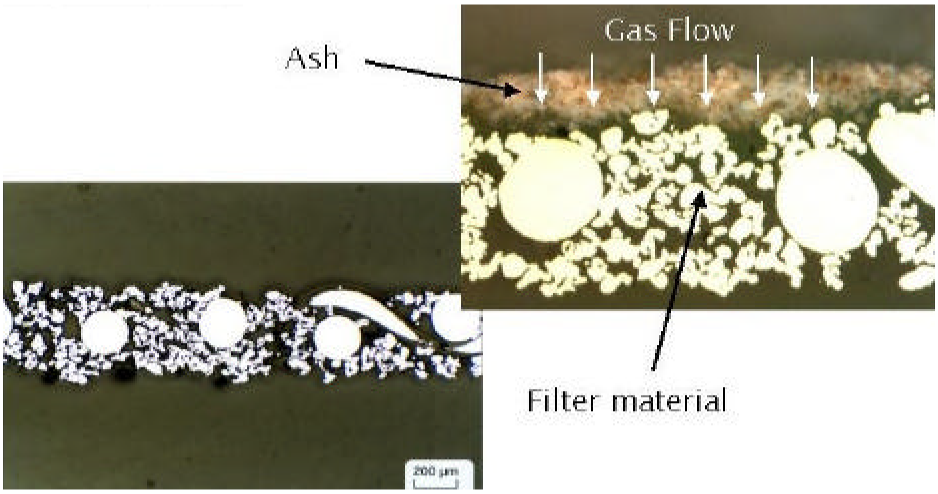


Ceramic Fiber

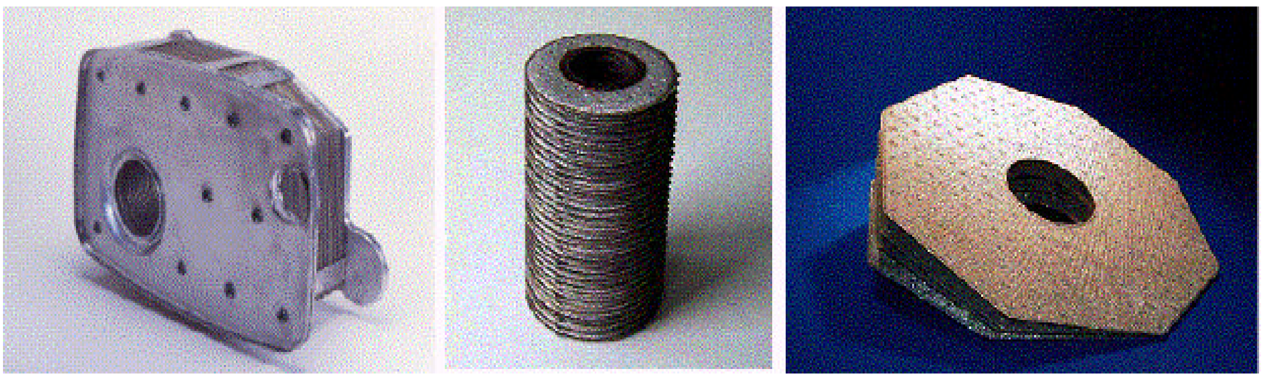


Ceramic Foam





Sintered Metal Filter - Orthogonal Cross Sections with and without Ash



Sintered Metal Filter - Design Examples

Filter Materials; Conclusions

- Cordierite is today the preferred material for mobile machinery because of the price advantage
- More robust Filter materials might be available at a lower price than today in the near future
- The Filter efficiency of most Filter materials is excellent (>90%)
- The existing risk of most Filter material damaging with overloaded Filters has to be minimized by an intelligent regeneration control strategy (see section 7.2)

7.2 Oxidation Regeneration Methods

All Filter types discussed require that the collected soot is either continuously or periodically oxidised (regenerated) to ensure that the gas flow passages are not blocked, or present an excessive restriction through the accumulation of PM. This would typically occur after a limited number of hours of engine operation without regeneration (typically approximately 10 hours). The main methods for achieving regeneration of PM Filters are discussed and the merits and demerits of each option identified.

7.2.1 Review of Regeneration Technologies

Filter regeneration methods may be summarised into three categories:

Passive system – The collected soot is oxidized continuously in order to keep the Filter free. If the chosen regeneration method is not effective because of unfavourable operation conditions, too much soot is accumulated, the backpressure increases dramatically and the risk of an uncontrolled soot burning is high.

Active / manual system – These systems rely on the intervention of the equipment operator to initiate the regeneration process which typically involves the use of external devices to generate the conditions necessary for regeneration. An example is the exchangeable Filter systems used on some forklift trucks where the Filter is removed and regenerated off-board using various methods such as activation of the oxidation process by electrical heating or fuel burner. Another approach is on-board regeneration through periodic connection to an external heat source.

Such systems impact on the utilisation capability of the machine and the cost of supporting machine operation. They are typically applied only when there are controls to ensure that the correct procedures are applied by the operators, e.g. compliance with local Health and Safety requirements, or site regulations enforced by monitoring. Retrofit PM Filters that have been applied to construction equipment are often active – manual systems.

These systems are liable to be defeated by operators and are vulnerable to damage through failure of operators to implement the regeneration procedures when required; this results in excessive soot build-up and uncontrolled regeneration with extreme temperatures.

Active / automatic system – Systems integration approach whereby the exhaust gas temperature or the Filter surface temperature is managed so that regeneration events are initiated before the exhaust back pressure is allowed to rise excessively.

The active / manual methods cannot be considered as technological basis for the specification of PM emissions regulation standards for new equipment and, therefore, are not considered further in this report. This conclusion is consistent with a judgement by US EPA:: *Emission control systems which require an operator to physically perform alterations or additions to a system may not be effective in the field in achieving emission benefits, especially if not performing those acts would seriously damage engine performance.*

There are a number of technological options emerging for Passive and Active/Automatic systems that show some potential :

Regeneration Method		Description	Advantages	Disadvantages
PASSIVE	Pure Thermal	The high exhaust temperature at high load is used to burn the soot.		Requires: - Exhaust temperatures above 550^{o}C - Oxygen content in exhaust > 5 % These conditions are rarely met, so that the purely thermal regeneration will not be possible in most cases
	CRT	An oxidation catalyst upstream of the Filter converts nitrogen monoxide (NO) to nitrogen dioxide (NO_2) which acts as an oxidizing agent for the soot.	- Relatively simple system design - Many applications of mobile machinery with a medium load range are associated with exhaust temperatures that are within the optimal working range for CRT.	Requires: - Low sulphur fuel (< 50 ppm, preferred: <10 ppm) - NO_x / Soot mass ratio: > ca. 20/1 - Temperature range: 300-450^{o}C (at temperatures < 300^{o}C the oxidation of the soot is too slow, at temperatures > 450^{o}C the NO_2 dissociates again - The optimum temperature range of CRT excludes applications with low load and with continuous high load - Excessive NO_2 is emitted (problem fields: characteristic odour, lung poison, strict limit

				values at work places) - Overloaded Filters (by unfavourable temperature conditions or by use of fuels with too much sulphur) cannot be regenerated and need to be replaced.
	Metallic fuel additives	Metal containing additives (e.g. Iron or Cerium) are added to the fuel. Within the combustion process the corresponding metal oxides are formed, which are deposited together with the soot in the Filter. The soot in close connection with the metal oxides is burnt at lower temperatures (400-450^oC).	Relatively simple system design	- Exhaust temperatures >400-450^oC are not reached in many applications - The potential generation of not combustible particles (metal oxides) increases the maintenance requirements (ash cleaning more frequently necessary) - The correct dose of the additive has to be guaranteed (automatic system preferred) - Overloaded Filters (by unfavourable temperature conditions) can be destroyed by uncontrolled regeneration - Emission of potential metal compounds with unknown health effects
	Catalytic Filters	The surface of the Filter is catalytically coated (e.g. with platinum, cerium or vanadium), in order to facilitate the soot oxidation at moderate temperatures. The mechanism of this process is not yet	Relatively simple system design	- Function and Problems similar to CRT system, but effectiveness of regeneration slightly lower - The thick soot layer in overloaded Filters impairs the catalytic function

		completely understood: a mechanism of direct interaction between the solid surfaces of the soot and the catalyst is questionable because of low number of possible contact points. More probable is an NO_2 mechanism similar to the CRT system.		
A C T I V E / A U T O	Full Flow Burner	By combustion of Diesel fuel with a burner operated in the full exhaust flow of the engine the exhaust temperature is increased to 600-700°C, so that the soot is burnt within a few minutes. In order to achieve the necessary temperature increase also with unfavourable engine conditions a burner thermal power output comparable to the engine rated power and a fast control is needed.	- With an active burner system a regeneration can be achieved with almost every engine operation. Therefore, it is an ideal solution for the wide application ranges of engines in mobile machinery. - No secondary emissions - No overloading of Filters and uncontrolled regeneration possible, as long as there are no failures of the active system	- High system complexity and cost implications (problematic especially at low series numbers) - Safety aspects have to be carefully handled - Nominal increase in fuel consumption
	Exhaust temp. increase by late com-bustion	By using late secondary injection of Diesel fuel into the combustion chamber of the engine the fuel energy is converted mainly into exhaust temperature. Engines with common rail injection systems can realize this.	No special burners or components needed	- Increased entry of fuel and soot into the lube oil as a consequence of the late combustion - Lubrication property of the oil film has to be maintained - Achievable temperature increase not sufficient for soot regeneration

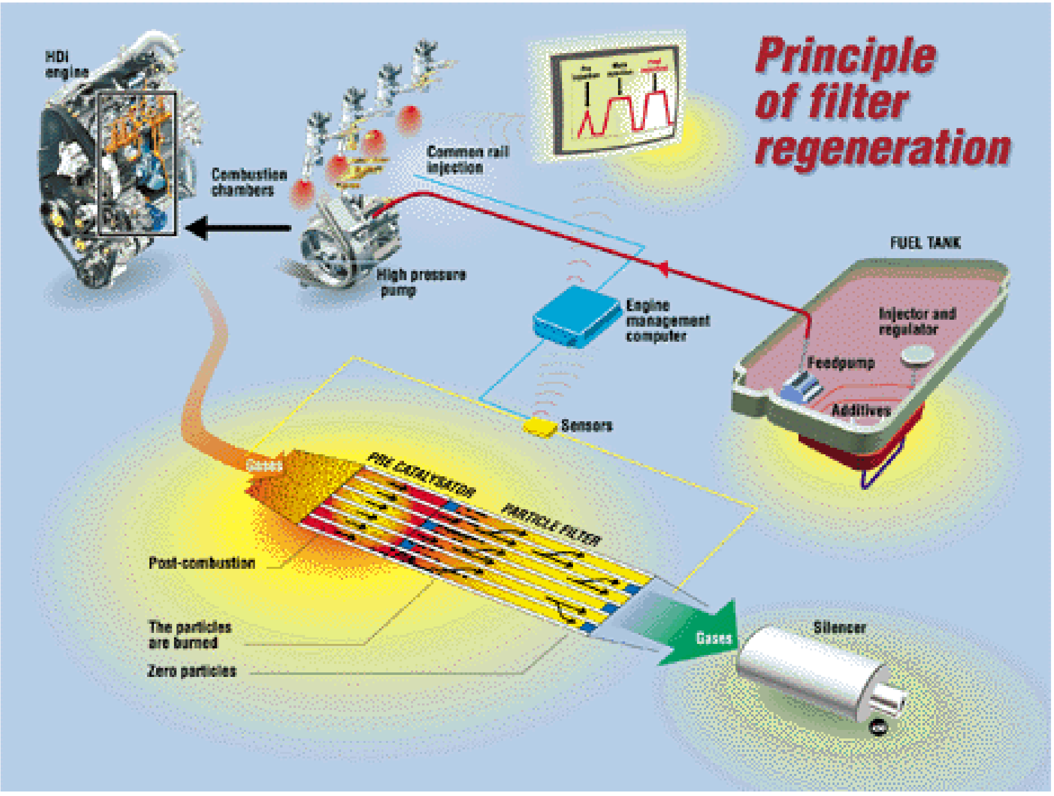
	Late injection without com-bustion and by oxidation at a catalyst	If a portion of the fuel is injected so late, that it is not burnt in the combustion chamber, this fuel can be oxidized at an oxidation catalyst. This oxidation process at the catalyst is also associated with heat formation and temperature increase.	No special burners or components needed	If too large fuel quantities are oxidized at the catalyst, this means a too high thermal stress and strongly reduced life expectance. Therefore, the increase of the exhaust temperature by this method has to be restricted to 150 to 200°C.
	Combination of both methods to increase the exhaust. temp.	- Late combustion by post injection (exhaust temperature engine out ca. 400°C) - Additional post injection without combustion + oxidation at the catalyst - With the resulting exhaust temperature of 600°C from both steps a thermal soot regeneration is possible	No special burners or components needed	Sophisticated control mechanism needed, much application work to be done (only practicable for large engine series, e.g. Peugeot system which uses fuel additives as well)
	Passive regener-ation and active temp. man-agement	These methods need a minimum exhaust temperature (CRT, catalysed Filter, fuel additives). It may also be used for engine applications, where these temperatures usually are not reached. To increase the temperature the post injection as described above may be used	This method may be an alternative to the burner system for a wide application in mobile machines.	As this (moderate) temperature increase is needed during long operation times, a significant increase of the fuel consumption is possible, in any case much more than the fuel consumption increase with the full flow burner system, which has to be activated only once every ca. 10 hours.

Note: A PM Filter system which has received public awareness is introduced by Peugeot on a limited number of its passenger car models (Fig. 2). This system is partial active – automatic and applies a sophisticated systems integration approach with a combination of regeneration methods:

- CRT method (catalyst in front of the Filter)
- Metallic fuel additive (Cerium)
- Late fuel injection (common rail) combined with other means to increase exhaust temperature (engine out + catalyst to be above 600 °C)

Even applying such a regeneration strategy, regeneration is not guaranteed under all conditions with the system including a driver warning light indicating imminent Filter blocking and advising the need for highway driving to prevent this occurrence. The level of systems integration associated with could only be contemplated on an economic basis for high production volume products such as passenger cars. The Peugeot system uses SiC substrate for the Filter which is a high cost option.

Fig. 2 : Peugeot PM Filter System



7.2.2 Incomplete Regeneration by Oxidation - Ash Accumulation

The regeneration processes discussed in the above Sections relate only to the removal of accumulated soot by oxidation. However, during engine operation, a Filter also collects ashes from the exhaust stream. These ashes are formed from inorganic constituents of the fuel and lubricant which cannot be burnt either during the engine combustion event or subsequently in the Filter regeneration process. The main source of this Filter ash is lube oil additives; in cases were fuel additives such as Iron or Cerium are applied to catalyse the Filter soot oxidation process, these contribute significantly to Filter ash accumulation.

Over a period of engine operation ash deposits gradually accumulate in the Filter and the flow restriction gradually increases; the flow restriction observed after each regeneration would show an incremental increase. It has been calculated, and also demonstrated from testing, that even for a low oil consumption (e.g. 0.2g/kWh) Filter function may be impaired during operation to the extent that cleaning to remove the ash is necessary.

The amount of the ash accumulation and therefore the needed washing frequency can be reduced with the help of the following developments:

- Further decrease of the oil consumption of the engines
- Development of engine oils with lower ash content (today's engine oils contain 1.3 –1.8 % ashes. For the future the mineral oil industry is working on oils with 0.7 – 1.0 % ashes at a comparable oil quality level.

It should be recalled that the oil consumption can considerably increase during engine life and that the cleaning frequency of the Filter will increase for old engines.

Development work on new Filter materials is ongoing, and one of the aims of such developments is to achieve a certain permeability for ashes, of course without too much losses of Filter efficiency for soot. Filter solutions that obviate the need for flushing of ash materials would, of course, be preferred but no such solutions have yet emerged that combine this attribute with acceptable PM Filterping efficiency.

7.2.3 Filter Failure – uncontrolled Filter Regeneration

The regeneration process of soot oxidation is an exothermal reaction and the amount of heat released is a function of the quantity of soot contained in the Filter. If the Filter soot loading achieved before regeneration is allowed to exceed a certain level, the oxidation process can proceed in an uncontrolled manner with the generation of very high temperatures in the Filter. These high temperatures will result in damage to the Filter by softening the ceramic substrate. The melting point of Cordierite is 1400^{o}C, leading to complete Filter destruction. The soot loading should not exceed 5g per litre of Filter volume to ensure controlled regeneration.

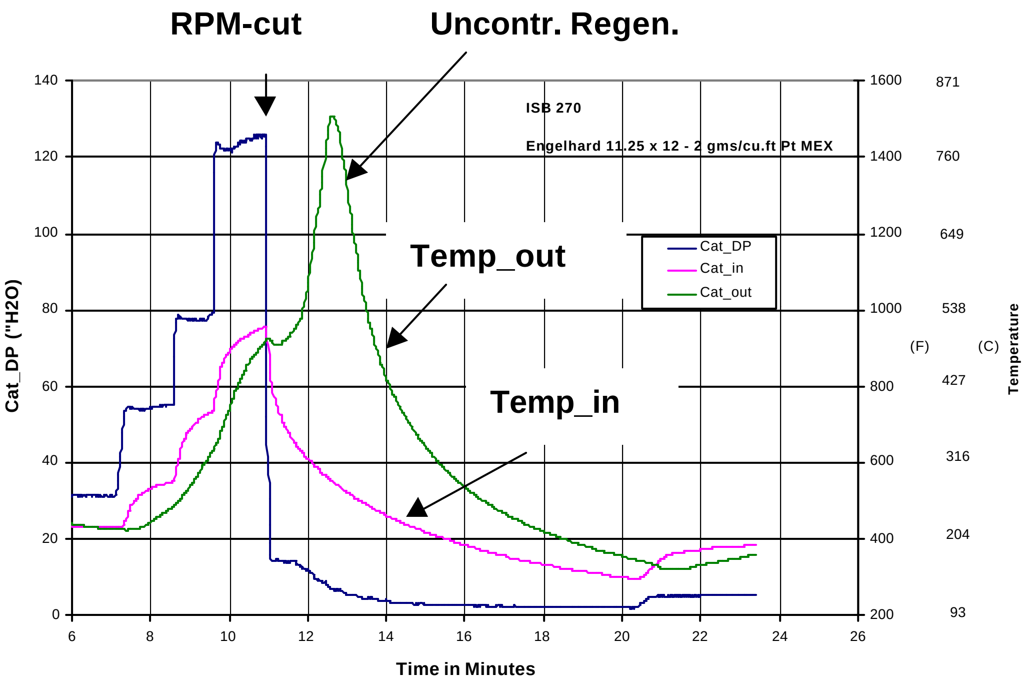


Fig. 3 : Measured Exhaust Temperature Profiles during Uncontrolled Regeneration (Reference: Cummins)

An uncontrolled regeneration event is recorded in the exhaust temperature history measurements presented in Fig. 3. This shows Filter entry exhaust temperature progressive increasing from a relatively low level in response to changes in engine speed and load demand. The Filter is loaded with soot and when the exhaust temperature reaches a certain level an uncontrolled regeneration is triggered, evidenced by the spike in the temperature of the exhaust gas exiting the Filter.

Fig.4 shows images of Filters that have experienced uncontrolled regeneration with the consequence of damage to the substrate necessitating replacement of the Filter.

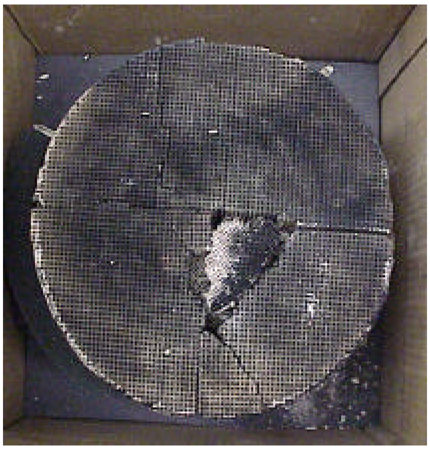


Fig. 4 : Substrate Damage from Uncontrolled Regeneration:
(left) High Temperature Melting; (right) Fracture from Temperature Gradients

7.2.4 Regeneration Methods: Conclusion

- Manual regeneration systems create operational burdens for machine operators which will result in a reluctance of machine owners to purchase equipment with such devices, or, in the absence of enforcement monitoring, removal of the devices from equipment.
- With passive regeneration systems (CRT, catalytically coated Filters, fuel additives) the regeneration will not function adequately with many applications of mobile machinery, especially with low load operation.
- Passive Filters can provide the base for an active – automatic regeneration system by active management of exhaust gas temperature, for example through the use of post injection strategies with electronically controlled fuel injection systems. However, this generally results in a fuel consumption penalty and entails significant complexity in the monitoring and control systems. This technology solution shows potential but requires significant further development to achieve the required functionality and subsequently, significant efforts to integrate and validate in non-road machine applications. The most technically mature system in respect to offering true active – automatic regeneration capability is the full flow burner. Existing systems are used in some low production volume, niche applications. The current designs are complex with inherently high cost. They have not been proven in a wide variety of non-road machines. While showing good promise in terms of performance, it still has to be established to what extent the system cost can be reduced in volume production, and the practicality of integrating such systems into NRMM.

7.3 Monitoring and Control of PM Loading and Filter Regeneration

7.3.1 The Electronic Control Unit for Active Systems

The control of the Filter functions can be done in a separate control unit or preferably in the control unit of the engine. The control unit has to take care of the following functions:

- Handling of sensor signals (backpressure, temperature)
- Calculation of the Filter load with soot and with ashes
- Start of the regeneration process at a certain soot load
- Control of the exhaust temperature during the regeneration process.
- Assessment of the regeneration success
- Warning to the operator, if the soot load is too high after unsuccessful regeneration attempts
- Warning to the operator, if the ash load requires Filter maintenance
- Log file of events and error messages

7.3.1.1 Criteria for the Induction of a Regeneration: Calculation of the Soot Load

To avoid an excessive soot loading the Filter has to be regenerated in certain time intervals. The use of fixed time intervals is not to be advised, as the soot loading may differ very much (depending on the application, on maintenance and on possible problems of the engine). Instead the regeneration has to be triggered, when a certain amount of soot is reached in the Filter.

The soot loading of the Filter can be assessed by the measurement of the Filter backpressure taking into account other relevant parameters as exhaust mass flow, exhaust temperature, dimensions of the Filter, dimensions and structure of the Filter channel walls and the ash loading. To calculate the soot loading from all these parameters the flow processes have to be modelled, and at least parts of this mathematical model have to be incorporated in the control unit.

7.3.1.2 Calculation of the Filter Loading with Ashes

The Filter loading with ashes can be deduced from the backpressure build-up after regeneration. Of course the possibility of a not complete soot regeneration has to be taken into account and plausibility checks of the calculated ash load are needed. If the ash load exceeds a certain level (around 30 %) the operator is informed about the maintenance need (exchange of the Filter for ash cleaning within the next weeks).

7.3.1.3 Control of the Regeneration Process

To burn the soot, the exhaust has to be heated up to ca. 600-700 ^{o}C for some minutes. To achieve this relative small optimal temperature range with all engine operation conditions, the amount of the additional energy (e.g. burner power) has to be controlled very fast. The most unfavourable engine condition is high speed and low load (full burner power necessary), whereas at full load of the engine the exhaust temperature is already so high, that a relatively low burner power is needed. Fast changes between these extremes can occur and require a corresponding fast burner control.

7.3.1.4 Communication between the Control Units of the Engine and the Filter

Many interactions between the control units of Filter and engine are necessary. For the calculation of the Filter load engine data are needed, e.g. from speed and load the exhaust volume flow can be derived using the corresponding mapping data. Alternatively the exhaust volume or mass flow can be directly transferred from the engine to the Filter control unit. The knowledge of the flows is also necessary during the regeneration process in order to control the burner power. On the other side data may also be transferred in the other direction (from the Filter to the engine control unit), e.g. to increase the engine out exhaust temperature with the post injection method.

7.3.2 The Control Unit with Passive Systems

It has to be stated clearly, that also passive regeneration systems need a control unit. Also with passive systems the actual Filter load with soot and ashes has to be known, in order to assess the correct Filter function.

The control unit has to take care of the following functions:

- Handling of sensor signals (backpressure, temperature)
- Calculation of the Filter load with soot and with ashes
- Control of the exhaust temperature at low engine load (e.g. with post injection, if this option is available)
- Assessment of the success of the continuous regeneration
- Warning to the operator, if the soot load is too high
- Warning to the operator, if the ash load requires Filter maintenance
- Log file of events and error messages

The differentiation between soot and ash loading is much more difficult with passive than with active systems, because the condition of a completely regenerated Filter (no soot, only ashes) exists seldom or never. If the average backpressure increases slowly over long operation times, it cannot be directly distinguished, if this is caused by the ash effect or by a worsening of the soot regeneration conditions. A solution might be to simulate the chemical processes of the passive regeneration, to compare the calculated values with the measured backpressure and to deduce the ash content from the discrepancies between calculation and measurement.

7.3.3 The Role of the Control Unit; Conclusion

- A control unit is needed for systems with active and passive regeneration as a part of engine/equipment integration
- The most important tasks of the control unit are:
    - Assessment of the Filter condition
        - Filter loading with soot and ashes
        - Error diagnosis, message to the operator for maintenance need
    - Control of the regeneration process
    - Interpretation of sensor signals (backpressure, temperature)
- These complex control functions are only partially available in existing Filter systems. A high effort is still needed to improve these control functions and to test them in different applications. These improvements of the control functions are very important to achieve reliable systems with low maintenance need. Considerable research and development work remains to be done. This could surface consequent unknown problems related to applications.

8. PM Filter Technology – Consideration of NRMM Engine Requirements

Typically an engine model that is developed and offered for NRMM applications is used in a wide variety of equipment types and experiences a broad range of operating conditions. An aftertreatment system that is offered as original fitment by an engine manufacturer must function under all possible conditions that may be encountered in any machine. This requirement dictates that an Active/Auto PM Filter system, fully integrated with the engine controls, is the only practical option for specifying a PM Filter for a general-purpose engine for industrial and agricultural equipment applications.

The contention that an Active/Auto Filter system is required for non-road machines is demonstrated in the following. This is achieved by examining the possibility of identifying the specific operational requirements of a non-road engine and specifying a PM Filter system with narrower range capability than a active/auto system. The study indicates that non-road engines experience a broad and diverse range of modes of operation in a variety of machine applications and uses. As a result, there is no defined operating pattern that can be applied as a criteria for specifying a PM Filter system.

8.1 Machine Duty Cycles

Section 7.1 indicates that exhaust gas temperature is the key parameter in facilitating Filter regeneration through the oxidation of the accumulated soot. A minimum exhaust temperature is required for the soot oxidation reactions in the Filter (the temperature threshold depends on whether there is a soot + oxygen reaction, a catalysed soot + oxygen reaction, or a soot + nitrogen oxide reaction). The temperature of the exhaust gas emitted from a diesel engine is a function primarily of engine load, assuming that the possible strategies indicated in Section 7.2 to artificially elevate the temperature are not being applied.

Therefore, the load cycle requirements presented by the range of machine types that incorporate a particular engine model, will be a key determinant in Filter technology selection. The assessment must consider not only average load factors, but must interrogate load – time histories to establish whether the frequency and duration of operation at exhaust temperatures above the regeneration threshold, and maximum time interval between such periods of operation, is satisfactory to ensure continued operation of the engine without Filter clogging.

A number of examples are provided to indicate the broad range and complexity of load cycle requirements for NRMM engines, and in particular, the unfavourable conditions with respect to exhaust gas temperatures to support Filter regeneration.

8.2 Determining the Load vs. Time Characteristics

An engine manufacturer, if attempting to specify a PM Filter system without the broad range capability of an active/auto device, would need to establish the worst-case condition with respect to the load (and, therefore, exhaust temperature) characteristic. This worst-case needs to be determined on the basis of accommodating all modes of operation that an engine may encounter in the multiplicity of equipment types into which the engine model will be incorporated. The difficulty is illustrated by the following.

8.2.1 Typical Load Cycles for Selected NRMM Equipment Types

This section describes the influence of different nonroad applications on the exhaust temperature, in order to demonstrate the problems for passive Filter systems, which depend on a minimum exhaust temperature.

Examples of machine operating characteristics with respect to engine speed and load, and exhaust gas temperature are presented in this section. These illustrate, on the basis of a limited number of examples relative to the large variety of NRMM, the unfavourable exhaust temperature conditions for Filter soot oxidation. In particular, these indicate the limitation of passive Filters in the context of NRMM engines.

Example 1

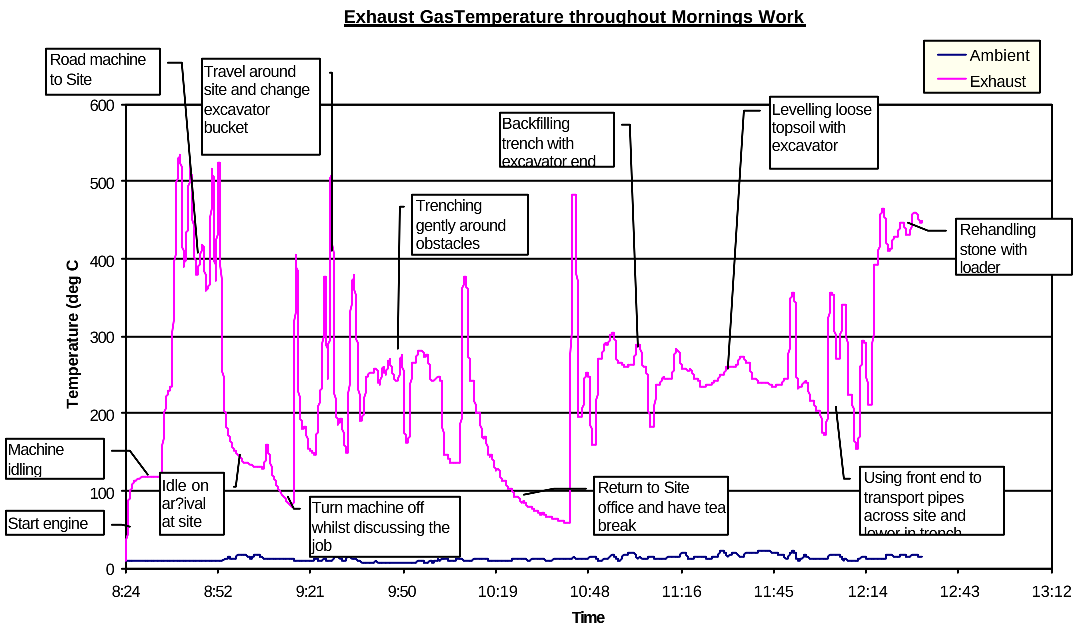


Fig. 5 : Typical on-site operation of a backhoe loader, 56kW, 2200rpm
Reference: JCB

Fig. 5 presents measured exhaust gas temperature data recorded during an actual period of operation of a backhoe loader. This shows that a variety of modes of operation are experienced by this single machine during a short monitoring period. It suggests that a relatively high proportion of operation is at low/medium load conditions. This sample data indicates that the periods of high load operation are of insufficient duration to support regeneration of a simple passive Filter.

Example 2

Similarly Fig. 6 shows exhaust gas temperature data recorded for a period of actual machine use. In this case the application is an Aircraft Tow Tractor. This profile shows a characteristic which is even less conducive to supporting Filter regeneration with a very low average load cycle and with only very short duration excursions to high load operation. Again a simple passive Filter would not be satisfactory for this application.

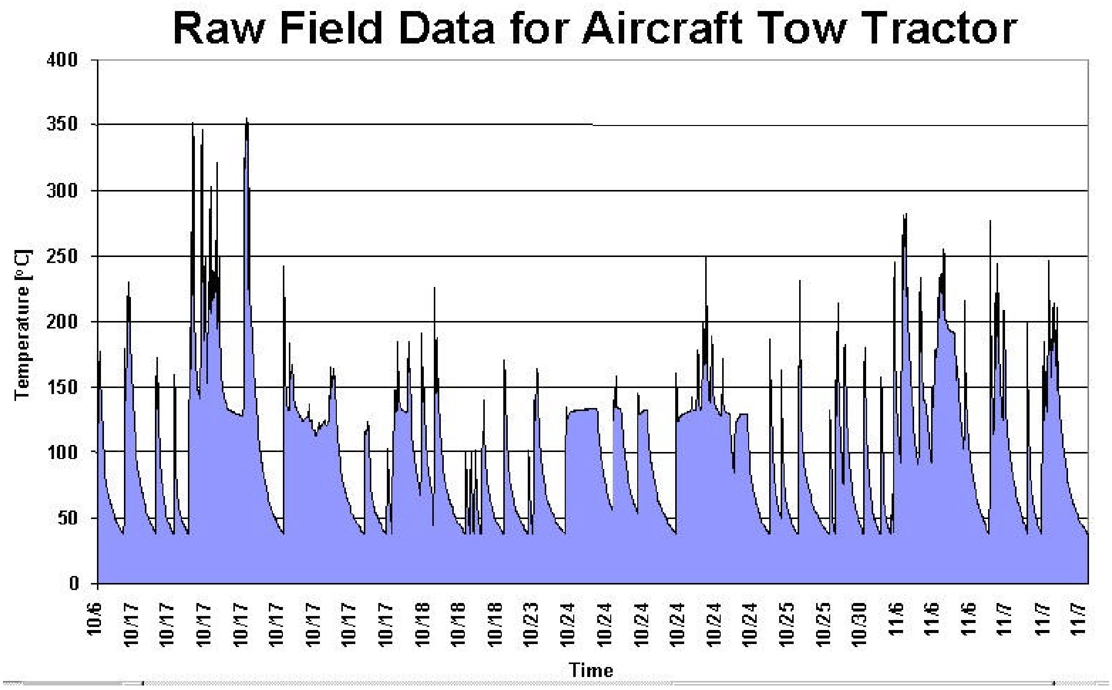
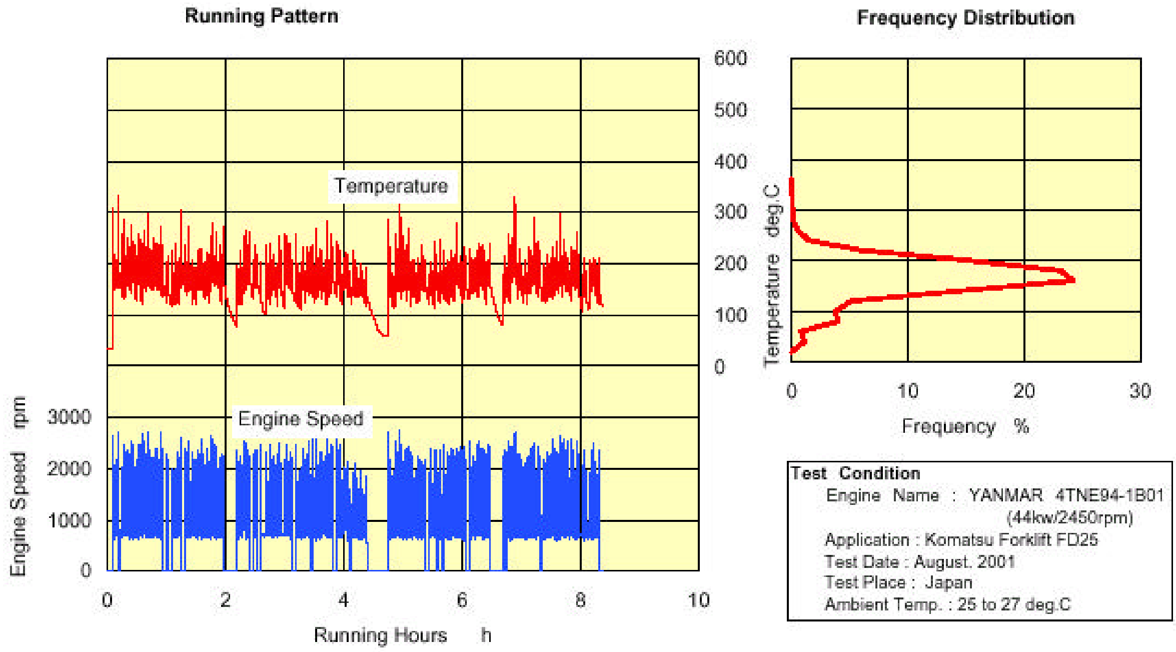


Fig. 6 : Exhaust gas temperature vs. time of a machine in operation
Reference: Cummins

Example 3
Reference: YANMAR

Figs. 7 and 8 present exhaust temperature history profiles recorded from two small diesel engines (44kW and 25kW) operating in comparably lightly loaded applications; a forklift truck and a trailer refrigeration unit. An average exhaust temperature of approximately 180 ^{o}C is recorded for the forklift with a frequency distribution approximating to a normal distribution with a low standard deviation value. This application would not support the regeneration of a passive Filter.

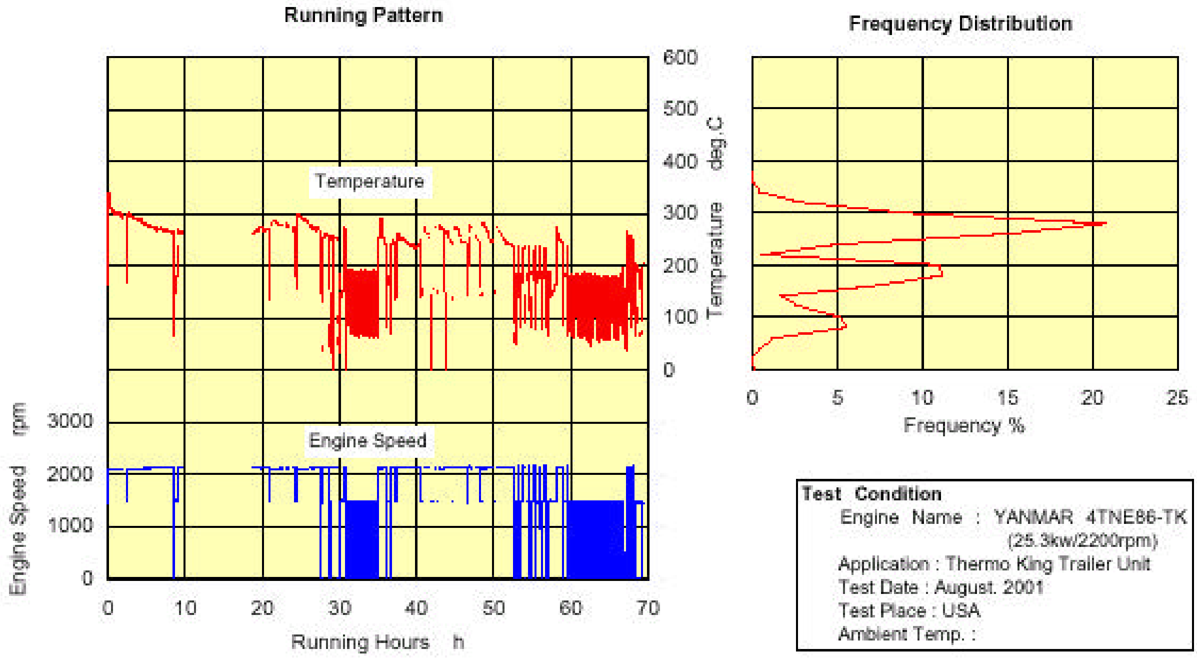
Fig. 7 : Exhaust Gas Temperature of Fork Lift



The exhaust temperature profile for the refrigeration unit represents a more complex frequency distribution with a significant portion of operation at exhaust temperatures up to 300 °C. However, again the exhaust temperature is insufficient to support regeneration of a passive Filter, particularly considering that the data was recorded in summer at relatively high ambient temperatures. At lower ambient temperatures, lower exhaust temperatures would be recorded due to the lower temperature of the engine intake air, and also due to the lower demand on the refrigeration unit.

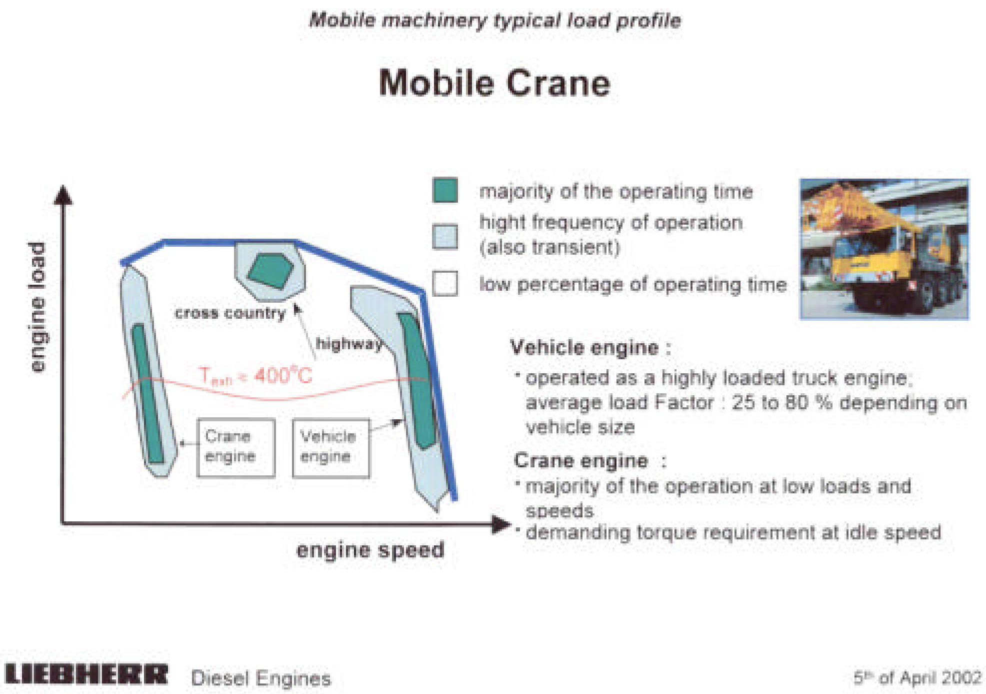
While the typical exhaust temperature in the summer was 280 °C (maximum: 350 °C), these values decreased to 170 °C and 200°C in the winter. Of course this large difference can be explained mainly by the lower cooling necessity and lower engine load in the winter and only partly by the ambient temperature influence on the combustion process.

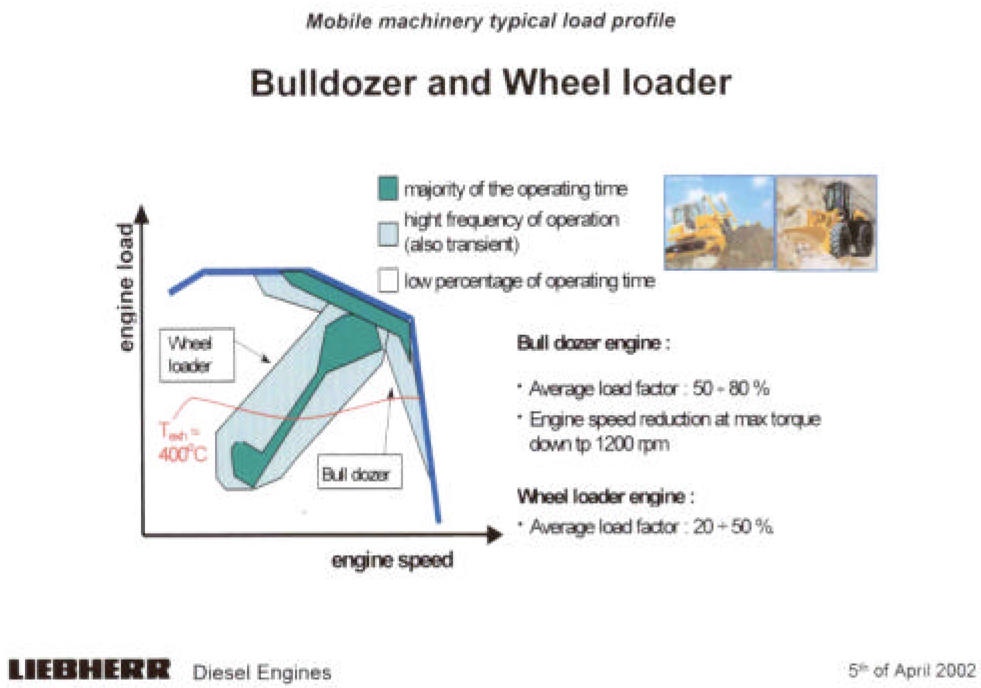
Fig. 8 : Exhaust Gas Temperature of Refrigerator Unit

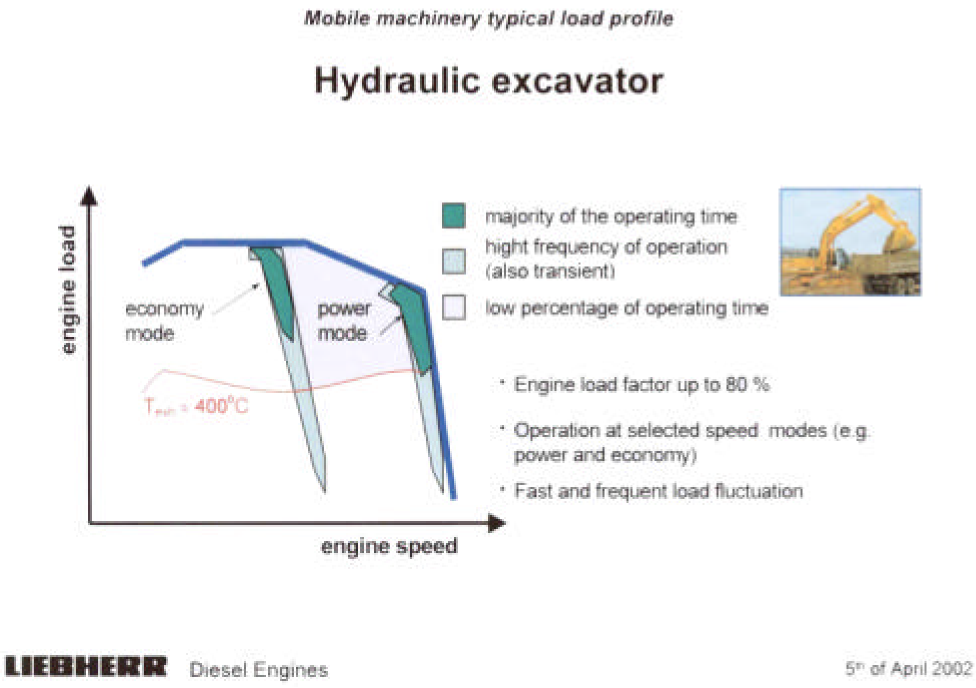


Example 4

Figures 9-11 : Exhaust gas temperature fields for various types of machinery and their operation
<u>Reference: LIEBHERR</u>







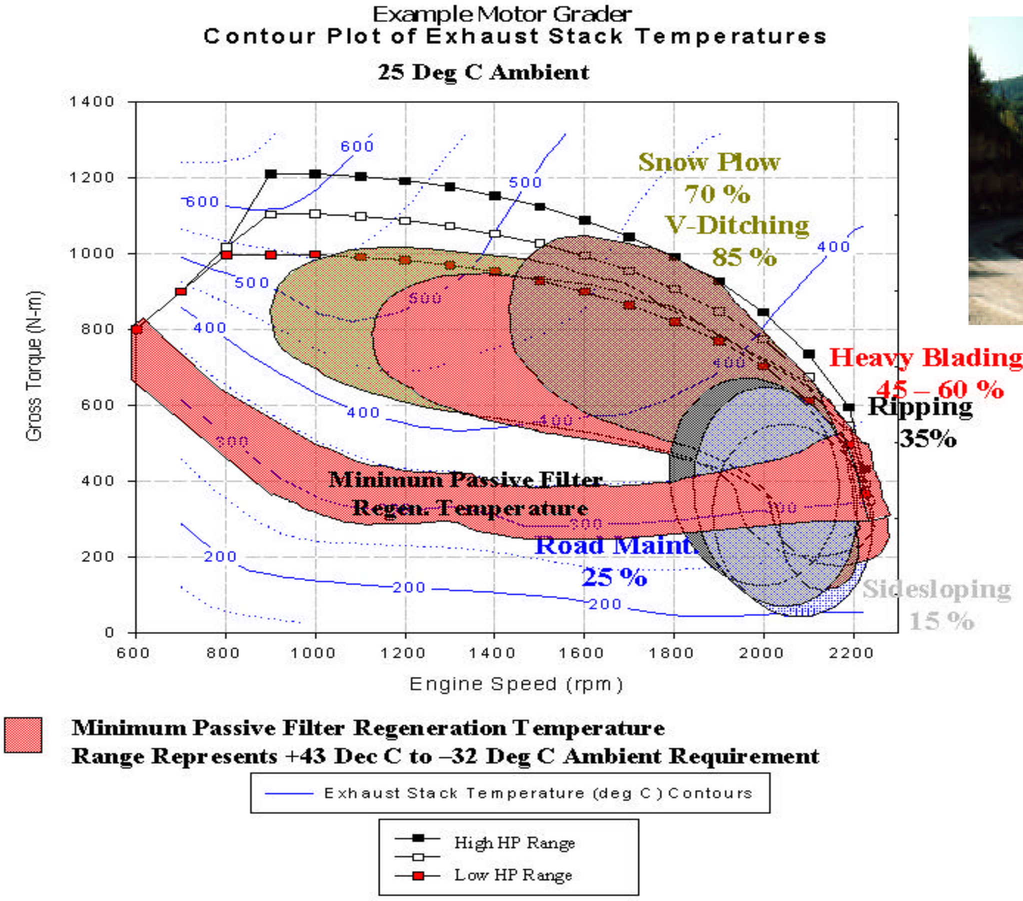
Example 5

Fig. 12 shows the typical areas of operation with respect to the engine speed – torque characteristic of a motor grader for the different functions for which this machine is typically employed. Engine exhaust gas contours are plotted and the minimum regeneration temperature for a passive Filter indicated. This case exemplifies the difficulty in characterising a typical load cycle even for a specific machine type since a machine can be applied for a multitude of purposes.

The data also indicate the limitation of a passive Filter system in regard to the capability to regenerate under all conditions of use of the machine. While the data presented is aggregated information and, does convey sufficient information to determine conclusively the applicability of a passive Filter, it does indicate insufficient exhaust heat would be available to support regeneration of a passive Filter during certain operating modes such as road maintenance or ripping.

Fig 12 : Torque-Speed-Temperature Plot for a Motor Grader

Reference: CATERPILLAR



Example 6

A project to characterise the operating cycles of non-road machines was conducted by US EPA (with additional tests commissioned by the EC) recently as part of a programme to develop a Non-Road Transient Cycle for the certification testing of NRMM. This involved measurement of actual in-use engine operation of machines. While exhaust temperatures were not recorded during this exercise, and the focus related to operating modes where PM generation is more prevalent (i.e, load increase transients), the recorded load cycle characteristics provide actual operational data that can be analysed in relation to the load conditions required to support PM Filter regeneration. The result of such an analysis is presented in the table below. An average exhaust temperature has been derived from the averaged speed and load values.

The analysis shows the large variation of exhaust temperatures for different nonroad applications and even for different operation modes for one given application. It also indicates that, on the basis of the averaged data, several of the applications would not be suitable to accept a passive PM Filter. It should be noted that while some of the applications would support a passive Filter on the basis of average exhaust temperature data, further analysis of the instantaneous load profile would be required to confirm the suitability. Additionally, it should also be considered that the measurements do not necessarily reflect typical operations for all machines within a particular category (see note below).

Estimation of Filter Temperatures for the EPA Nonroad Transient Cycles

	Average Speed	Average Load	Average Power	Average Exh. Temp.	Possible Regeneration Methods:		
					CRT	Cat. Coat. Filter	Fuel Addit.
	%	%	%	deg C			
Agricultural Tractor Cycle	78,8	78,5	72,3	381,3	yes	yes	yes
Backhoe Loader Cycle	35,6	25,2	17,6	241,4	no	no	no
Crawler Tractor Cycle	58,1	60,2	46,6	313,7	yes	no	no
Excavator Cycle, productivity type	86,2	69,8	71,7	404,7	yes	yes	yes
Arc Welder Cycles:							
Arc Welder Typical Operation	85,8	19,0	18,2	404,0	yes	yes	yes
Arc Welder Typical Operation	86,5	18,9	18,2	406,1	yes	yes	yes
Arc Welder High Speed Transient Operation	84,5	21,8	20,7	399,6	yes	yes	yes
Arc Welder High Torque Transient Operation	93,0	25,7	25,2	427,1	yes	yes	yes
Skid Steer Loader Cycles:							
Skid Steer Loader Typical Operation	67,1	29,8	28,2	343,1	yes	?	no
Skid Steer Loader Typical Operation	64,7	18,4	19,3	335,5	yes	?	no
Skid Steer Loader High Speed Transient Operation	75,1	38,8	35,1	369,0	yes	yes	no
Skid Steer Loader High Torque Transient Operation	68,2	32,8	28,6	346,8	yes	no	no
Wheel Loader Cycles:							
Wheel Loader Typical Operation	33,1	34,4	24,4	233,2	?	no	no
Wheel Loader Typical Operation	37,6	39,0	28,7	247,9	no	no	no
Wheel Loader High Speed Transient Operation	45,1	45,3	33,4	272,1	no	no	no
Wheel Loader High Torque Transient Operation	47,8	48,5	35,6	280,8	?	no	no

Reference: Analysis of US EPA published data prepared by DEUTZ

Note: Specific Limitation of Agricultural Equipment (see also Section 8.4.2)

Agricultural tractors are produced in a range of sizes to perform a wide range of functions and can be fitted with a wide range of implements. They are used to pull various pieces of equipment, and in many cases to provide auxiliary power to various attachments; for example, to a power harrow or baler through a mechanical Power Take-Off, or hydraulic power for ploughs or for trailer brakes. The lower power tractors, represented especially by the 37 - 75 kW power range, are subject primarily to handling and transportation tasks, and are often used on dairy farms. While some agricultural tractors do operate at high load factors, for example those used primarily for tasks such as ploughing, the average load cycle is not typical for all machines. Indeed, the average load cycle for agricultural tractors ranges from 10% to 90%. The operation of most agricultural tractors would not provide the necessary exhaust temperature characteristic to support regeneration of passive Filters.

8.2.2 Engine Idling Duration

The worst-case engine operating condition for achieving a PM Filter regeneration event is at engine idling, since this represents the lowest exhaust temperature condition. Unfortunately, non-road machines can experience extended periods of operation with the engine idling. The figure below presents data showing the proportion of machine operation that was spent at idle. This data was acquired by a particular machine manufacturer (VOLVO) that incorporates a data-logging feature within the electronic management system for all machines equipped with electronically controlled engines. It, therefore, represents real in-use operation as a reliable indicator of extent of engine idling that will need to be accommodated by an exhaust aftertreatment system.

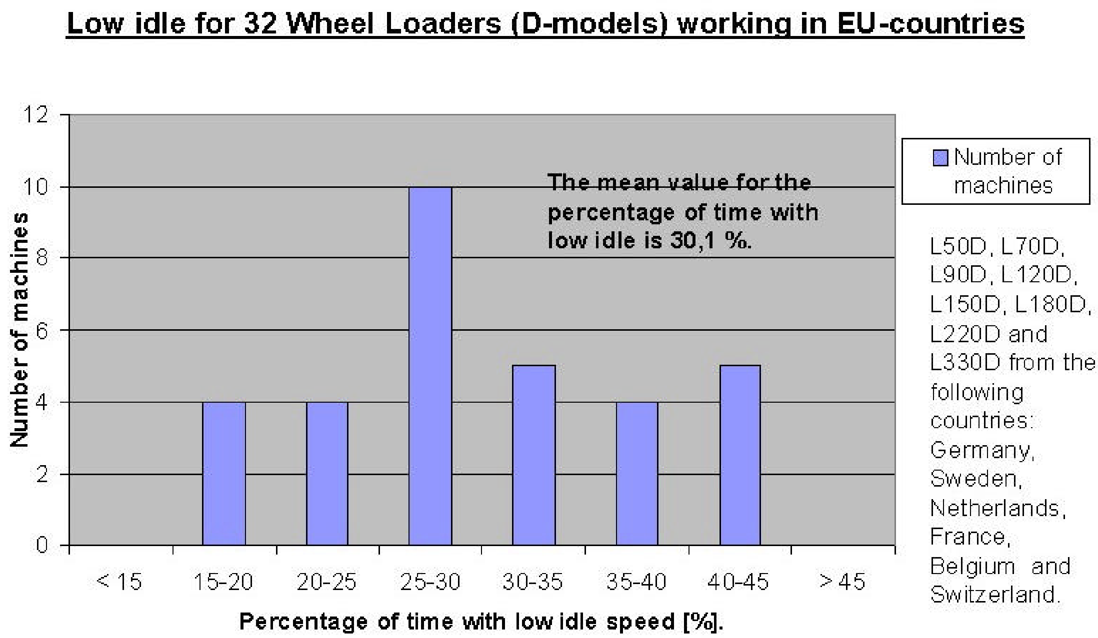


Fig 13 : Percentage of idle operation of a typical wheel loader
Reference: VOLVO VCE

The Filter system will have to be functional also during the worst-cases of the given idle portion values, i.e. 40-45 %. Other applications may have even higher idle portions. As the exhaust temperature in the low idle is only 100 -150 ^{o}C, passive systems cannot regenerate under these conditions.

The low exhaust temperatures achieved during idle operation can result in unburned hydrocarbons from fuel and oil condensing in the exhaust system and accumulating in the Filter. These hydrocarbons are released from the Filter when load is applied to the engine after a prolonged idling period, resulting in a period of high concentration of hydrocarbons in the exhaust stream. Such problems have been experienced by operators of machines fitted with PM Filters. This problem can be addressed by exhaust temperature management capability of an active/auto system but remains a problem for passive Filters.

8.2.3 Multi-Application Machines

The data presented in Section 8.2.1 indicate, on the basis of a small sample of the vast range of different nonroad machines, the broad range of load cycles for which NRMM engines are applied. The simple illustration of here below supports the point more graphically. This shows that, even for a particular basic machine type, there are many functions to which it can be deployed. In this case, by attaching different working tools, a wheeled loader can be converted into a forklift, a logging machine, or a crane; there are a number of additional attachments that could be listed.

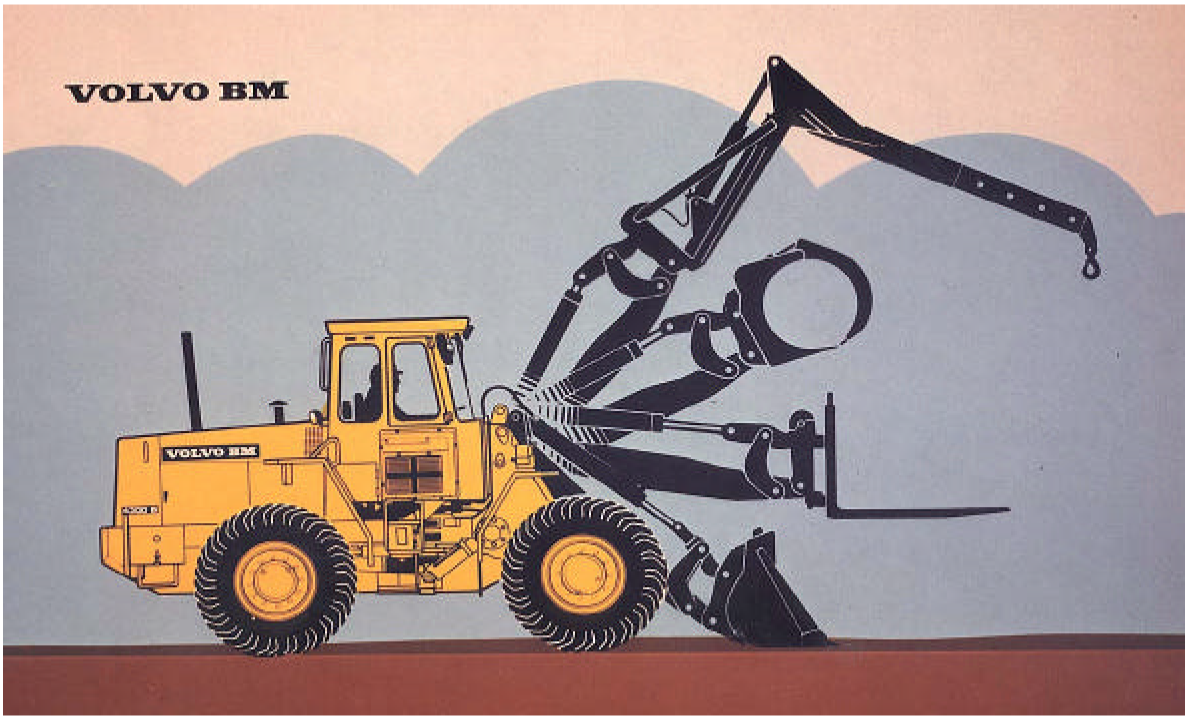


Fig 14 : The broad Variety of Working Tools to be attached to a Basic Machine
Reference: VOLVO

As these possible different applications for one machine are associated with different load factors and exhaust temperatures, passive Filter regeneration methods, depending on a sufficient exhaust temperature level will fail with certain attachments.

8.3 Ambient Temperature Influences

The exhaust temperature at the Filter is influenced by the ambient temperature, and so a passive regeneration system can function without problems in the summer, while it fails in the winter. As a very low failure rate is necessary to avoid excessive warranty costs, the worst case situations (winter in Finland and Sweden) have to be accommodated within the capability of the Filter regeneration function.
Reference: Yanmar

The Fig. 15 shows an example of the summer/winter differences:

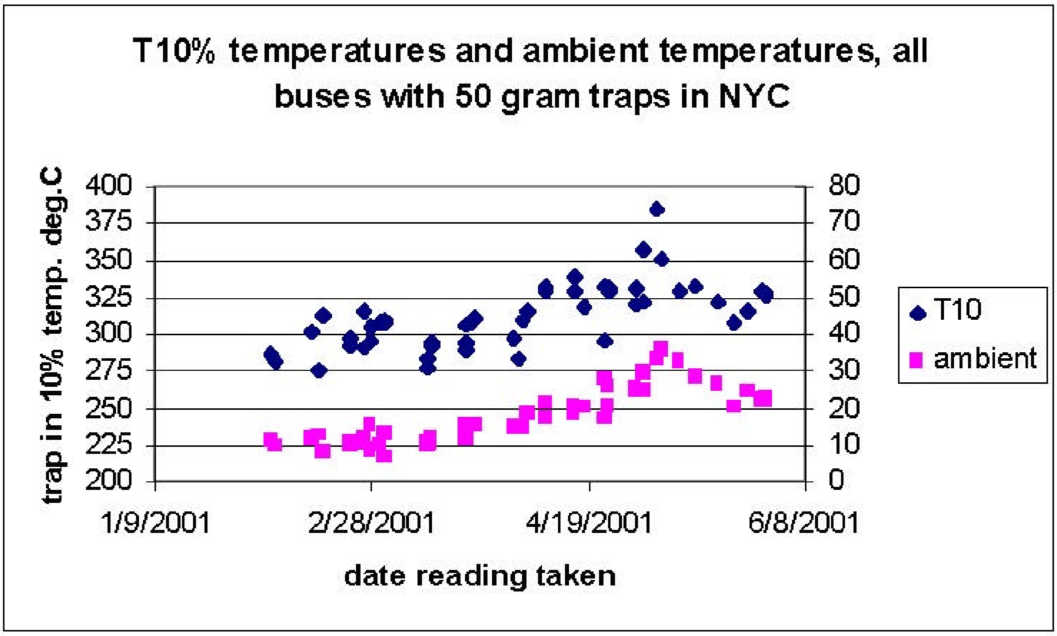


Fig. 15 : Ambient temperature influence on regeneration temperatures of catalytically coated Filters during bus operation New York City (T10: Filter temperature, at which regeneration conditions are met at 10 % of the load cycle)
Reference: Cummins

From summer with 30°C to winter with (only) 10°C the T10 temperature falls from about 325 to below 300°C, which can be a cause for failures in the winter.

An even more dramatic summer/winter difference was reported by Yanmar regarding engines in refrigerators for trailer units (see also Example 3, Fig. 7 and 8).

8.4 Comparison of Parameters effecting PM Filter Selection between NRMM and On-Road HD (Heavy Duty) Truck Applications

8.4.1 Duty Cycle

The engine operating cycle for on-road trucks is relatively well defined in terms of both the average load and the frequency distribution about the mean. The core operating range of a typical on-road truck engine is significantly narrower than that required from a general-purpose nonroad engine. The key criteria in developing the engine and transmission specification for truck applications, is maximisation of fuel economy. This results in specification being defined to provide the predominance of operation in the engine speed range of 1400 – 1500rpm, and with an average load factor of 30 – 40%.

While truck engine operation is, in general, well defined by the nature of the function of the task performed by the vehicle, and the fuel economy incentive to specify engine size and transmissions ratios relative to the vehicle weight, there are some heavy-duty on-road applications that also present problems for passive Filter regeneration. For example, problems are being experienced with passive Filters fitted to city buses on some routes. Applications such as refuse collection trucks also present challenges due to long periods of low-load operation. Satisfactory solutions have not yet been developed for all such on-road applications.

8.4.2 Design Integrity and Packaging Requirements

Many nonroad machine applications present a significantly more hostile operating environment than that experienced by on-road trucks. Construction machines generally suffer higher levels of vibration and shock loadings than would be typical for a truck. In the case of some machines the vibration loading would be many times higher; for example, a tracked bulldozer experiences very high shock loadings from blade/shovel impacts as well as those generated from the tracks when manoeuvring on hard surfaces.

Machines have to operate in varied environmental conditions including very hot, very cold, dusty and wet conditions. The engine compartments in non-road machines are often highly enclosed and with limited compartment volume due to the need to provide a machine design architecture and packaging that provides maximum machine functionality and performance. Integrating PM Filters into the design of many machine types will be challenging due to limited engine packaging space available, the difficulty in managing under-hood temperatures together with consideration of the need to provide a high level of visibility for the operator. The packaging issue is particularly severe for the <75kW sector of the market, where the high volume, low cost, relatively simple machines, are very compact for manoeuvrability.

Additionally, due to the variety and diversity, inevitably there are particular niche applications that present additional difficulties relating to packaging and operation. An example is harvesting machines which are unique seasonal machines typically operating in very dusty and hot environment. Even today fire on combines and farm lands are a problem where sometimes the adjacent highways have been closed. Phases in emissions regulation show an increasing temperature of turbocharger, exhaust manifold and ducts for the same power and engine size. This is a real challenge to keep the fire hazard within acceptable limits. The introduction of aftertreatment would further increase the threat of fires.

9. Review of In-Field Experience with PM Filters

Filters are being used today, and have been used for some time, on certain applications of NRMM. This limited use of PM Filters has generally been in response to work place regulations concerning ambient air quality applying, for example in case such as indoor operation or for tunnelling machines. In some cases, Filters have also been used when required by job tender conditions. In general, the requirement to use Filters in such circumstances has been satisfied by retrofitting PM Filters to machines. Active / Manual systems have been used primarily. An example is the forklift truck application which accounts for a high proportion of NRMM Filters used to date, where off-board regeneration often is used. Passive systems have also been used on some construction equipment to satisfy job site requirements. However, the specification of passive Filters in these cases is based on detailed knowledge of the specific work cycle of the individual machine.

While it has been explained in Section 8 that the type of systems that have been applied in the field are not a suitable technological base for setting a general engine type approval emission standard, some valuable experience has been gained in the application of Filters to NRMM. The following presents reports from an engine manufacturer (DEUTZ) that also produces PM Filters and has supplied Filters for some non-road applications. Information from another engine manufacturer's (Cummins) extensive in-field trials of PM Filter systems is discussed. A further report is included from an equipment manufacturer (LIEBHERR) that is a major supplier into Switzerland where Filters are required on a number of job sites. A note on general experiences relating to the use of Filters on machines operating on certain construction sites in Switzerland is also provided.

9.1 Report from DEUTZ

The DEUTZ DPFS (Filter system with full flow burner and automatic operation by an electronic control unit) was sold as retrofit system with a number of 1020 in the years 1994 to end of 2000. The experiences with these systems in real operation conditions and ongoing developments regarding hardware and regeneration strategy limited the failure rate within the warranty period to 3 %. Filters sent to DEUTZ for ash cleaning after 5000-7000 hours exhibited reduced Filter efficiency in 15 % of the cases and needed to be replaced. Further developments are needed to reduce the failure rate.

Additionally DEUTZ sold 5000 manually activated Filter systems (external regeneration with an electrical heater) for forklift trucks. With these systems even lower failure rates were achieved (1 % within the warranty period).

An ash cleaning procedure was developed and successfully applied. But is not an automatic procedure and can only be used for small numbers up to now.

9.2 PM Filter Field Trials by Cummins

Cummins conducted an in-use study of PM Filter system technologies in conjunction with the US Navy. The investigation included the following elements:

- Screening 80 vehicles for operating characteristics
- Data logging 20 vehicles of various types for exhaust temperature distributions: Truck; Bus; Industrial; Military; Stationary
- Installing passive soot Filters on 8 vehicles
- Installing active HC soot Filters 2 vehicles

- Installing active electrical soot Filters on 2 generator sets

The PM Filter system technologies investigated in this study were:

- low PM passive Filter
  5 gram Pt (Platinum) loading, 350 ppm fuel sulphur
  (assumed to require > 700 deg.F for 10% (370 ^{o}C))
- high PM passive Filter
  50 gm Pt loading, 15 ppm fuel sulphur
  (assumed to require > 600 deg.F for 10% (315 ^{o}C))
- low tech HC injection system
  50 gm Pt pre-cat, HC injection, 15 ppm fuel sulphur
  (assumed to require > 500 deg.F for 10% (260 ^{o}C))
- high tech HC injection system
  50 gm Pt pre-cat, HC injection with evaporator, 15 ppm fuel sulphur
  (assumed to require > 400 deg.F for 10% (205 ^{o}C))
- burner, electrical, or off-line

(Note: HC injection is a method of increasing the exhaust gas temperature by hydrocarbon (fuel) injection in front of a catalyst)

The study concluded that of the applications investigated:

- only 25 % can be handled with low PM passive Filters
- only 30 % can be handled with high PM passive Filters and ultra low sulphur fuel
- only 55 % can be handled with low tech HC injection system
- only 75 % can be handled with high tech HC injection system
- 100 % can be handled with burner, electrical, or off-line

9.3 Report from LIEBHERR

LIEBHERR installed since 1998 on customers request different Filter systems on hydraulic excavators, wheel loaders and mobile cranes according to legal requirements in Austria, Germany and Switzerland (tunnels, indoor, highly populated regions). Specific problems experienced :

- Ceramic Filters with fuel additives:
  - Dosage of fuel additives
  - Cleaning and disposal of additive ashes
  - Filter blockages
- CRT Filter
  - Excessive NO_2 emission
  - Availability of <50 ppm sulphur fuel for nonroad use
- Ceramic block with electric regeneration
  - Long regeneration time with electric regeneration
  - Electric power supply necessary

9.4 Swiss Experience

The use of PM Filters on construction equipment on certain job sites in Switzerland has been presented by some as an indication of the feasibility of more widespread use of Filters on NRMM. The basis of the Swiss experience is that the installation of PM Filter is a mandated condition for a machine operator tendering to do work on the sites. These requirements were introduced to address specific large construction sites in areas with specific air quality problems, and in the context of significant previous experience gained by the Swiss authorities in introducing Filters for tunnelling machines used in extensive tunnelling projects in Switzerland.

The Swiss experience of Filters for NRMM is based on an extensive, multi-faceted programme that was carefully considered and executed. Most, if not all, of the Filter systems used are retro-fitted to the machines. Very significant technical effort has been involved in assessing the operation of individual machines in order to identify the specific solution that can accommodate the operating characteristics of individual machines. To this end a complex 'Applications Oriented Filter Selection' guide was developed and applied. This lists 12 PM Filter technology options with a 9 parameter selection criteria to determine the appropriate option for a specific machine/operation.

The systems predominantly use active regeneration mechanisms. Some of the systems place a significant burden for the operator, especially the systems requiring off-board regeneration. However, with the high level of supervision and inspection by the agencies involved, operators complied with the requirements.

The Swiss experience clearly demonstrates the large technical challenges associated with specifying PM Filters for non-road machines. These challenges can be addressed, as the Swiss experience shows, under very specific circumstances. The circumstances in the Swiss experience were:
(a) retrofitting systems on individual machines predicated on knowledge of the machine operation;
(b) the customer of the construction project prepared to pay the extra cost associated with the capital cost of the systems and the reduced operational efficiency of the machines;
(c) rigorous inspection and maintenance enforcement programme.

The Swiss experience showed the following specific problem items:

- The assessment of the suitability of a passive system for a certain application is difficult. A wrong decision is associated with extremely high costs.
- Electricity to burn out the Filter elements is not always easily accessible.
- For large engines 2 or even 4 Filters have to be used in parallel
- Restriction of visibility cannot always be avoided.
- Retrofit programmes are suffering from a lack of responsibility and insufficient involvement of the engine and machine manufacturers. They are therefore not comparable to the solutions discussed in this paper, where the Filter is an integrated component of the engine and the machine.

The experience gained in Switzerland with the use of PM Filters does not confirm the technical feasibility of PM Filters in relation to regulating a PM Filter forcing emissions standard for the Type Approval of all new NRMM equipment. Conversely, it clearly indicates that this could not be achieved with the best available PM Filter technology available today. The Swiss experience confirms that today it would not be possible to specify a passive regeneration PM Filter for a non-road engine to be offered for general-purpose, multi-application use.

Complementary information on the Swiss experience is included in an EMA summary report presented in Appendix 1.

10. Cost Analysis

References: DEUTZ , LOMBARDINI

The cost data given in the following table are estimates, if reasonable production numbers of about 30000 Filter systems and more can be achieved annually by the engine manufacturer. The prices quoted are those from engine manufacturer to equipment manufacturer.

There are certain costs which are related to the individual system (engine and Filter price) and other costs that are related to the application of an engine-Filter combination to a certain equipment type (engineering, field test and documentation). Of course these additional costs are not effective for small equipment volumes, whereas they have no significant effect for large volumes, as can be seen from the table. The documentation costs are related to the integration of the Filter to the machine regarding operation manuals and CAD. Not included in the cost table is a redesign of the machine, which can be associated with even higher costs.

Effect of engine numbers per machine type on the filter related costs

		Engine power, kW			
		20	50	100	200
Price of the engine	Euro	2000	3500	8000	14000
Price of the filter *)		1500	1500	2500	3500
Engineering costs for application *)		15000	15000	15000	15000
Field test with 4 machines *)		110000	120000	140000	180000
Documentation *)		100000	100000	100000	100000
Filter related costs:					
10 machines per year	% of engine price	300,0	177,1	95,0	67,1
20 machines per year		187,5	110,0	63,1	46,1
50 machines per year		120,0	69,7	44,0	33,4
100 machines per year		97,5	56,3	37,6	29,2
200 machines per year		86,3	49,6	34,4	27,1
500 machines per year		79,5	45,5	32,5	25,8

*) Costs roughly estimated
*) Calculation with 5 years stability

These figures correlate exactly with those evaluated independently for the power range below 37 kW. Considering the amount of engines produced for certain application and even assuming series production of Filters, the cost of the integrated system engine + Filter will double, and even more for the bottom end of engine power.
Reference: LOMBARDINI.

Today's costs for retrofit systems are e.g. € 9000.- for 70kW engines and € 25000.- for 500kW engines (DEUTZ figures). In order to achieve the projected costs indicated in the above table, enormous cost reductions from today's levels are required. This will necessitate a large investment of resource to design and validate cost reduction features and will require a sufficient lead time period for these activities.

Maintenance, running and recycling costs needed are not yet included in the table. The useful life of the Filter and the ash removal intervals need to be further experienced.

The small volume numbers are typical for nonroad equipment as experienced by engine manufacturers on their markets.

The average production quantity of Yanmar or Lombardini engines for one equipment model is around 400 units annually. This number may fall down to below 200, if the few models with more than 5000 units annually are excluded.

The average production quantity of DEUTZ engines for one equipment model, for which the mentioned Filter application costs is needed, is only around 300 units annually. This is an average value and there are many applications with much lower volume numbers, for which these high application cost place a significant burden.

Appendix 1 EMA Report - PM Filter Experience in Switzerland

Rush to PM Filter Mandates Not Always Smooth: The PM Filter Experience in Switzerland

The Swiss Clean Air Act (LRV 1998, app. 2) provides the basis for a major improvement in air quality and mandates that "emissions are to be reduced in as much as technically, organizationally and economically justifiable…" (read: BAT, Best Available Technology). Independently of this, the SUVA (Swiss Accident Protection Agency) issued the 2001 workplace emission directive mandating the use of engine emission particulate matter(PM) Filters on equipment used in sensitive applications like tunneling, indoor operation, and other workplace related emissions. Both directives are legally binding in Switzerland and now require operators to retrofit nonroad construction equipment with PM Filters for all applications.

The responsibility to implement the regulation is delegated to Cantonal authorities, but the task of adding PM Filters to the equipment falls squarely on equipment owners. Progress on retrofitting equipment has proven more difficult than anticipated and is still behind schedule. Because of this, the Swiss Contractors Association (SBV) has asked for a moratorium; the government denied the first request, but the SBV reportedly continues to discuss the legal aspects of the implementation process.

To learn more about the difficulties encountered as a result of the Swiss mandate, several interviews were completed with general construction contractors. The following comments outline some of the problems experienced in attempts to meet the Swiss retrofit mandate and are indicative of today's in-use experiences with various vintage machines. While many of the problems and difficulties will likely be resolved with future technological advances, others are inherent in the nonroad equipment design and may not be solved in the short term.

Construction Contractors Concerns

- Today, the equipment owner is totally responsible for compliance and the retrofit system, including its proper functioning. Owners also bear the operational consequences in case of malfunction and suffer the financial consequences. This situation is unacceptable to the contractor since he supports the complete burden of the regulatory mandate.
- The Government publishes a comprehensive list of approved Filters available for use. However, contractors claim that the list insufficiently covers the broad array of end uses of the engine and machine applications. In addition, many entries are based upon laboratory studies and manufacturers claims that have not been adequately tested under real-world conditions.
- Contractors believe that PM Filter retrofit solutions must be developed with the co-operation of the engine manufacturer and the Filter manufacturer, and integrated into the specific application by the vehicle manufacturer. More active participation is needed to develop integrated solutions to fit all applications that can then be purchased with confidence.
- Filter manufacturers claim a life expectancy of 4 – 6000 hours. In practice, however, equipment owners indicate that a significant portion of the Filters on NRMM machinery is very vulnerable to vibration. They report that the Filters often last less than 1000 hours and are very expensive to replace. The Filter core in the photo here below is a sample; the replacement cost for this element is CHF (Swiss Francs) 5000.- (€ ~ 3400.- or $ ~ 3000.-).

- Retrofit installation and operating costs are generally more expensive than anticipated. An analysis of a mixed fleet of 85 units showed that acquisition and installation cost of PM Filters for trucks vary from 40 to 100 CHF/kW, construction machinery runs from 100 to a high of 260 CHF/kW *(€ 58 –153)* and costs for speciality machines (i.e. drill rigs, compactors, excavators) are even higher. PM Filter costs for earth-moving machinery is an average of 150.- CHF/kW *(€ ± 100.-).* Contractors documented costs of ~ CHF 3.- *(€ 2.-)* per hour, based on 2000 h/year for repair, maintenance (including laboratory) and parts for Filter system. The additional cost for low sulphur fuel (below 25 ppm) is 2 - 4 % depending on quantities purchased and geographical location. Filter systems requiring fuel additives may add 2 % to fuel cost. In addition, some Filter systems increase fuel consumption by several % points. Back-up pressure tends increases with Filter life, resulting in higher fuel consumption.

Filter core broken due to vibration at less than 1000 hours, replacement cost at least € 3000.-

Clobbered installation: long tubing from engine, heat losses, vibration

Restriction of rear visibility cannot always be avoided. In many cases, there is no other place for the Filters

Duplication of Filters increases costs, i.e. on larger, higher horsepower V8 engines. Increases maintenance and repair

- Maintenance of Filters is proving to be problematic. High variations in temperature and frequent low load operation complicate the operation, and maintaining adequate Filter performance becomes laboratory intensive and costly. The supervisor is challenged to safeguard the operation and maintain proper job conditions, which often are very tough, in rugged areas, lacking easy access. While regeneration works in tunnels, burning out of Filters is not allowed, the elements have to be brought outside to a cleaning station. Electricity to burn out the Filter elements is not always easily accessible.

- Quality and reliability of PM Filter systems is uneven and in some cases contractors had to completely replace installed PM Filter systems with others. In general, contractors are unhappy with the technical assistance and expertise provided by government and suppliers of equipment and PM Filters.

Important Factors to Consider

Swiss contractors have learned that complying with government mandates is not as simple as it appears. Selection of the appropriate PM Filter system for the specific equipment application is crucial. The wrong system for a given application can result in serious problems. Contractors offered the following advice:

- Select a Filter system that is designed for the engine, equipment, and operating conditions that you will encounter.
- Ensure that the Filter is appropriate for the exhaust gas temperature of the equipment to prevent Filter clogging.
- Select Filter equipment from reputable firms with adequate field testing to ensure performance.

NOTE: Once a Filter system is selected and installed to satisfy a particular machine operation, the application flexibility of the machine will be compromised by the limitation of Filter regeneration range capability; this is an important issue considering the multi-purpose nature of many construction machines.

Summary

The experience of Switzerland's contractors and equipment owners has not been satisfactory to date. They report many problems related to the use of particulate Filters in retrofit applications including premature failures, high installation and operating costs, and limited availability of proven equipment for all applications covered by the mandate. The Swiss experience provides an example of the need for government to proceed cautiously regarding mandates and the need to provide a thoughtful and comprehensive approach to the introduction of PM Filter technology. Although government regulations will seek to further reduce particle emissions, it is important for legislators, equipment operators, and engine and emissions control equipment manufacturers to work together to provide proven and feasible solutions to PM reductions.

Hans Gehrig
EMA Europe Office

July 2002

From: Suchecki, Joe [jsuchecki@enginemanufacturers.org]

Sent: Monday, November 25,2002 4:33 PM

To: 'comments@msha.gov'

Subject: EMA Comments on ANPRM Regarding DPM Exposure of Underground Meta l and Nonmetal

TO: Comments@msha.gov

FROM: Joe Suchecki
Engine Manufacturers Association

Via E-mail
RECEIVED
11/25/02
MSHA/OSRV

DATE: November 25,2002

RE: MSHA Request for Public Comments on DPM Exposure of Underground Metal and Nonmetal Miners

Attached are comments by the Engine Manufacturers Association regarding the above referenced matter.

<<MSHA1125.doc>> <<EMA Report.pdf>>

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