DELIBERABLE D2400.5

TECHNOLOGY EVALUATION REPORT FOR
DIESEL ENGINE AFTER-TREATMENT SYSTEM
Summary

This report documents the technology survey and selection process that precedes the work leading to the electrified Diesel Particulate filter prototype, a deliverable within WP2400. This document is divided into three main parts, corresponding to a general review of DPF technologies, their ranking and an application-specific evaluation leading to the selection of a technology candidate for the WP2400 work that follows.

The first part consists of a general review of the state-of-the-art Diesel Particulate Filter (DPF) technologies, with special emphasis on DPF regeneration, technically and energetically the most demanding aspect of DPF operation. It is shown that the rather extensive history of DPF development for non-hybrid Diesel vehicle powertrains now provides a wide array of DPF technologies for consideration. The problems in Diesel particulate emission control which have motivated this long history of development are also discussed.

In the second part, the technologies and their characteristics identified in foregoing review are discussed and condensed into a tabular comparison of candidate DPF technologies with respect to their performance, durability/reliability, relevant cost metrics and compatibility with electrification. This comparison highlights some of the factors that have lead to the current mainstream status of some DPF technologies but also identifies technical factors that make certain less developed technologies interesting candidates for the current objectives.

The third part of this document attempts a more application-specific review of particulate control for Diesel hybrid commercial vehicles. The evaluation weighs more heavily on factors such as the potential energy efficiency of electrical regeneration and compatibility of DPF power requirements with electrical facilities available on the hybrid vehicles considered. This closer inspection of available DPF technologies has lead to the selection of a DPF concept based on a metallic micro-fiber fleece material as the most promising candidate in line with the sub-project SP2000 objectives of demonstrating energy efficiency and operational advantages through the electrification of hybrid commercial vehicle auxiliaries. The investigation of this selection, which departs from the most established / conventional DPF technologies in current mainstream use, is justified in terms of expected emission performance, energy efficiency gains and other important operational considerations which give the metallic fleece DPF relative merit particularly in terms of compatibility to the hybrid commercial vehicle platform.
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### Abbreviations – Acronyms

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>APU</td>
<td>auxiliary power unit</td>
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<tr>
<td>APTL</td>
<td>Aerosol &amp; Particle Technology Laboratory</td>
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<tr>
<td>AT</td>
<td>Aluminium Titanate</td>
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<td>CERTH</td>
<td>Centre for Research &amp; Technology Hellas</td>
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<tr>
<td>CLM</td>
<td>cross-linked microstructure</td>
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<tr>
<td>cpsi</td>
<td>honeycomb monolith cell density in cells per square inch</td>
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<tr>
<td>CRT</td>
<td>continuously regenerating trap</td>
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<tr>
<td>DOC</td>
<td>Diesel oxidation catalyst</td>
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<tr>
<td>DPF</td>
<td>Diesel particulate filter</td>
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<tr>
<td>HCV</td>
<td>hybrid commercial vehicle</td>
</tr>
<tr>
<td>IC</td>
<td>internal combustion</td>
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<tr>
<td>ICE</td>
<td>internal combustion engine</td>
</tr>
<tr>
<td>Re-SiC</td>
<td>recrystallized silicon carbide</td>
</tr>
<tr>
<td>Si-SiC</td>
<td>silicon-bonded silicon carbide</td>
</tr>
<tr>
<td>PM</td>
<td>particulate mass or particulate matter</td>
</tr>
<tr>
<td>PN</td>
<td>particle number</td>
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<tr>
<td>p.p.i.</td>
<td>pores per inch (measure of pore size/density for foam materials)</td>
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</table>
Introduction

One of the main goals of the HCV project is the reduction of the fuel consumption of the hybrid vehicles and therefore also the reduction of toxic exhaust emissions. Normally a diesel particle filter (DPF) is used to reduce the particle emission. This filter however uses fuel to be able to regenerate/clean itself by burning off the particles attached in the filter. The idea investigated in the work package WP2400 or more exact task T2450 is to find a solution for a DPF that would use the electrical energy to heat the filter and therefore save some fuel. The electrical energy should come from the regeneration energy.

This report will provide an overview and comparison of the available technologies for materials for e-DPF filters and also define the requirements for the material.

General Survey of Particulate Emission Control

The DPF has been applied to production vehicles since 1999 and is now standard equipment in most European Diesel passenger cars as well as all US and Japanese cars, with the prognosis that DPFs will remain an indispensable part of the diesel engine powertrain even beyond the non-hybrid / purely ICE powered Diesel vehicles. In the heavy duty sector, the DPF has also been widely implemented, both as OEM fitted equipment as well as in retrofit programmes especially for emission compliance upgrading of publicly managed fleets. While application of the DPF to heavy duty engines preceded passenger car applications, much of DPF development has been driven by performance requirements (and legislation) from the light-duty sector, with many technological results then being transferred back to the heavy duty applications (even to Diesel locomotives, more recently).

Diesel particulate filter materials and geometric configurations

During the last twenty five years, numerous DPF system concepts have been developed incorporating different filter media and geometric configurations. A partial list of the more prominent, commercially available and prototype filter media includes on the one hand extruded ceramic materials (such as cordierite, aluminum titanate, silicon carbide, mullite, etc.), and on the other hand metallic materials (such as sintered metal powders, non-woven fiber felts and metal foams). Less prominent media/designs, such as cartridges made of ceramic fibers/cloths as well as various types of ceramic foams, these often having their origin in filtration/separation applications in other industrial applications, have not been able to transfer well their specific properties to the automotive applications.

Some commercial (extruded ceramic) filter configurations that are very widely used, are shown in Figure 1.

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2 Clean European Rail-Diesel (CleanR-D) Project, 7th Framework Programme FP7-SST-2008-RTD-1, project website: http://www.cleaner-d.eu/
An estimated distribution of these materials on the global particulate filter market can be seen in Table 1.

Table 1. Estimated Utilization of Filter Materials for Hot Gas and/or Exhaust Cleaning

<table>
<thead>
<tr>
<th>Material</th>
<th>Utilization</th>
</tr>
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<tbody>
<tr>
<td>Extruded ceramics</td>
<td>70%</td>
</tr>
<tr>
<td>Ceramic fibres (wound and knitted)</td>
<td>25%</td>
</tr>
<tr>
<td>Sintered metals (granular or fibrous)</td>
<td>4%</td>
</tr>
<tr>
<td>All others</td>
<td>1%</td>
</tr>
</tbody>
</table>

Geometric DPF configurations include extruded honeycomb wall-flow monoliths, assembled parallel plate wall flow elements, cylindrical cartridges (based on fibrous structures), foam monolithic blocks and plates, and concentric tubular wall-flow elements. Some configuration examples of these are shown in Figure 2.

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4 Murtagh, M.J., “Diesel Particulate Filters (DPF): A Short Course”, Diesel Particulate and NOx Emissions Course (University of Leeds), Ann Arbor, MI, October 2002.
**Extruded ceramic wall-flow DPFs**

The wall-flow monolith honeycomb design, originally introduced in 1981\(^5\), still remains the most popular configuration since it exhibits a large ratio between the filter surface and the volume. This contributes to lower pressure drop and, more importantly, to a higher soot filtration efficiency. The wall flow monolith honeycomb filters are constructed out of an extruded square cell structure, in which channels are plugged at alternate ends forming a checkerboard pattern on each DPF face, as shown in Figure 3. The exhaust gases entering the filter channels are forced to exit through the porous walls into the adjacent channels, causing the particles to be trapped on and inside the porous walls. The dark arrows indicate exhaust gases with particles, and the lighter arrows the filtered exhaust gases.

As the particulate matter accumulates on the channel walls the pressure drop across the filter increases, thus, leading to increased back-pressure to the engine and deteriorated fuel economy. Hence, the regeneration of the filter, by removal of the soot, is an integral part of DPF operation.


\(^6\) Ibid.
Ash from the lube oil is also captured by the DPF during the operation of the filter. This ash is volumetrically a minor component of the total adhered material however it cannot be removed by oxidation (unlike the other particles) and therefore, over long periods of operation, accumulates inside the filter gradually. This causes an irreversible increase of the filter pressure drop. Improving the DPF tolerance to ash accumulation has occupied DPF development more extensively in the past 15 years. Especially after the implementation of fuel-additives with soot oxidation catalyst which has a great influence on the amount of ash residue. In order to increase the ash storage capacity of honeycomb filters a number of asymmetric cell designs have been proposed\textsuperscript{7}, resulting in commercial implementation of the octagon-square (“octosquare\textsuperscript{®}”), asymmetric square and hexagonal honeycomb structures. APTL-CERTH\textsuperscript{8} has supported the early development of some of these asymmetric designs through extensive study of their loading and regeneration behaviour using application-specific simulation tools.

In late 1999, PSA Peugeot Citroën presented the first diesel particulate filter system to be fitted as standard production equipment in a common rail, diesel engine passenger car\textsuperscript{9}. By 2007, thirteen of the PSA Group’s vehicle models were fitted with the extruded “octosquare” honeycomb filter design, which was launched in 2004 by the Japanese DPF manufacturer Ibiden Co., Ltd. This design features increased ash storage capacity and filter durability, thus extending the servicing life of the DPF\textsuperscript{10}. Asymmetric channel geometry was eventually also adopted, in one form or another, by the other DPF manufacturers with large market share.

In terms of materials the filter substrate plays a very important role on diesel filter systems, since it affects both its performance and durability. Particularly important material properties include pore structure (filtration efficiency, pressure drop), melting point (durability), heat capacity and thermal expansion coefficient (resistance to thermal shock) and resistance to chemicals in the exhaust.

Cordierite and silicon carbide are the two most common materials used in commercially available filter monoliths. Cordierite is a MgAl-silicate, which is synthesized out of the natural raw materials kaolin and talc. This ceramic has the longest history as a DPF-material and was already in use as a catalytic converter substrate in mass production prior to DPF introduction. In 1978, Corning Inc. (Corning, NY) developed an extruded cordierite particulate filter to remove soot from Diesel emissions\textsuperscript{11}.

SiC filters were introduced in the 1990s, and the first large scale commercial application was the light-duty filter system for Peugeot cars, which was launched in the year 2000\textsuperscript{12}. Ever since, nearly all filters in

\textsuperscript{7} DieselNet Technology Guide, Online information service on clean diesel engines and diesel emissions, http://www.dieselnet.com/


\textsuperscript{12} Salvat et al. op. cit.
European passenger cars have been using the SiC material while cordierite has claimed a larger market share in the heavy duty sector. Variations of SiC materials include:

- Recrystallized SiC (Re-SiC), which has been used for DPF application by the companies Ibiden, Notox A/S and LiqTech A/S.
- Silicon-Bonded SiC (Si–SiC), developed by NGK in 2000.

Another material, which is a compound based on aluminum titanate, has been introduced with the commercial name DuraTrap AT® by Corning, shown in Figure 4. The DuraTrap AT® material was launched in 2005 on diesel passenger cars by Volkswagen in Europe, as an alternative to the silicon carbide in that market segment. The system uses an advanced ceramic material which, like cordierite, allows a monolithic DPF design. The Corning DuraTrap AT filter can be used in either catalysed or uncatalysed applications. Aluminum-titanate, more generally, is being considered for heavy duty applications due to its inherent thermal shock resistance allowing single piece monoliths to be used even for larger size DPFs.

![Figure 4. The Corning DuraTrap AT filter system.](image)

In a more recent development, GEO² has presented a unique process for high porosity composite DPF materials that combine the low cost of extrusion, used to manufacture high cell density honeycombs, with a so-called cross-linked microstructure (CLM) in the DPF walls. This microstructure, based on chopped fiber precursors, provides high mechanical strength despite the higher porosity and gas flow permeability attained. Several known specific oxide and non-oxide compounds have been extruded into honeycombs with the novel cross-linked wall microstructure (such as silicon carbide, cordierite and alumina) however the new material developed is the composite mullite (Composite-M)\(^\text{13}\). Although worldwide rights to this special DPF manufacturing process were acquired by Corning Inc. in 2009, no commercial application based on the CLM technology has emerged by now.

Other DPF designs and materials include:

Ceramic Fibers

Different types of high temperature ceramic fibers have been studied for various designs of DPFs. All of the concepts showed different properties compared to the honeycomb-shaped wall flow filters. In the early 1990s, 3M Inc. presented NEXTEL, a brand of a synthetic high temperature fiber, which was suitable for diesel exhaust soot particle reduction. 3M filters involved the use of filter cartridges as the building blocks of the filters. The working space of the cartridges was filled with the fibers. Three types of cartridges were presented: the basic one, the electric cartridge and the concentric tube pack. The basic one consisted of a perforated support tube. The electric cartridge differed in the necessary incorporation of an electric heater. The fiber support tube served as the heating element. The concentric tube cartridge possesses increased filtration area but it was not possible to integrate an electrical heater into it. Fiber filters have been commercialized to a much lesser degree than wall-flow monoliths, and with limited applications in off-road and stationary diesel engines.¹⁴

At the research level, APTL-CERTH designed and constructed a fibrous filter assembly (made from catalysed fibrous materials supplied by the Tech-in-Tex Textil GmbH and Jonson Matthey Plc.) during the European FP6 project ART-DEXA (G3RD-CT-1999-00016). Filter evaluation for filtration efficiency, as well as loading and regeneration behaviour, demonstrated relatively low filtration efficiency and high pressure drop as well as problems with material losses. Therefore, it was decided at the time not to pursue this particular technology beyond the ART-DEXA project.

Ceramic Foams

Coarse open-celled ceramic foams are made by the so-called replication technique out of polymer foams and they form a rigid network of uniform cells with more than 90% porosity. Due to some limitations of the formation process (the impregnation of the ceramic precursor slurry and excess removal from the polymeric scaffold) pore/cell size is limited. Both alumina and cordierite foam DPFs were tested in the 1980s showing nearly the same advantages as fiber-based systems.¹⁴ Due to low soot holding capacity, large filter volumes are needed with ceramic foams, and therefore their commercial introduction to diesel vehicles was never accomplished.

Foam based DPFs with higher cell density were investigated within the European FP6 project STYFF-DEXA (G3RD-CT-2002-00785). The aims of the project focused on better understanding as well as optimization of open cell ceramic foam materials for low pressure drop, high separation as well as regeneration efficiency in the filter. A very detailed understanding of the filtration behaviour of foam filter materials was gained via experimental work using the prototype materials from Centro Ricerche Fiat and also specialized computational models developed within the project. However, a viable implementation of a DPF system with foam materials was not found to be achievable due to both the relatively large minimum pore size and the lack of flexibility in shaping the material.

Sintered Metal

Porous materials made of high-temperature resistant metals (sintered metal particles or fibers) represent an alternative to ceramics. One of the first designs was introduced in the 1990s, by HJS Fahrzeugtechnik GmbH Co., which started the development of a filter material which uses a wire mesh support and is coated with sintered Fe–Cr–Ni metal particles. The filter showed good filtration efficiency, low exhaust-gas back pressure, and high ash storage capacity while offering good flexibility in the design of different filters. In 2002 Bosch acquired the basic technology for sintered metal particulate filters, as well as the worldwide rights for further development, manufacturing and sales of such filters for diesel passenger cars and light commercial vehicles from HJS. However, Robert Bosch GmbH in 2006 confirmed it is not producing this technology since there was no interest from the customers.

A modified form of the sintered metal sheet material was developed and produced some years later by PUREM GmbH for the heavy duty market. The PUREM material was manufactured in the form of dimpled sheets designed to maintain tight but constant spacing between the filter pleats\(^\text{15}\). This allowed sufficient compactness such that a light duty DPF of an acceptable volume could be constructed and tested within the European FP6 Project COMET (G3RD-CT-2002-00811). The latter project, in which Purem GmbH participated, also investigated the addition of soot catalyst coating on the sintered metal material. Three different sintered metal filter wall formulations and the soot and ash accumulation on them were evaluated. Long-term aging as well as rapid ash loading of filter samples was accomplished in order to investigate the effect on the soot catalyst and also on the filter structure. Since sintered metal filters depart from the honeycomb structure, development of appropriate simulation tools was a significant component of the evaluation process due to the additional degrees of freedom for internal flow and soot deposition profiles allowed by the pleated (folded) structure. This was achieved by APTL based on explicit computational representations of the filter pleat elements, provided by PUREM, and was validated on a full-scale SMF (light-duty size) against experimental loading and regeneration data\(^\text{16}\). The overall COMET project outcome was that good coating ability was achieved on the sintered metal pleat material and a sound computational basis was established for understanding the flow behaviour and soot deposits distribution in the pleated structure. However, a sensitivity of the catalyst soot oxidation function was found with respect to ash accumulation — the soot oxidation catalyst was gradually decoupled from the soot deposit layer and so catalytic activity was reduced. The PUREM GmbH sintered meal filter was applied to a number of production (heavy duty) vehicles manufactured by Daimler. However, at the time, no regard was given to the prospect of electrification and the DPF design was targeted to fuel post-injection regeneration.

NV Bekaert S.A. has also been developing, for more than 10 years, a range of metallic filter media, this time based on a non-woven continuous fiber mat with a three dimensional, felt-like structure. The


Bekaert fiber media consist of sintered Fe-Cr-Al alloy metal fibers\(^\text{17}\) which, due to the high porosity but greater filter wall thickness (in the range of 1000 – 1600 μm), tend to capture the Diesel particulates inside the medium and not just on its surface. Because of this functional characteristic, this technology enables large PM and ash holding capacities with a light-weight medium, while low pressure drop can be maintained. More importantly, the pleated filters are directly heatable for active regeneration since the fiber mat is conductive and can function as a resistance heating element. This advantageous function has so far been exploited commercially only in off-road applications\(^\text{18}\) and in after-treatment systems of APU’s on long-haul trucks and recreation vehicles. Applications to road vehicle powertrain DPF systems have been proposed but not carried over to widespread exploitation.

Emitec GmbH has developed the PM Metalit\(^\text{®}\) system consisting of bladed corrugated metal foils that are separated by porous sinter metal fleece layers\(^\text{19}\). This is a partial flow filter, which captures particulates coming out of the exhaust and it regenerates on a continuous basis with the help of NO\(_2\) in the exhaust. These filters exhibited low backpressure rise when loaded, which did not lead to an increase of fuel consumption due to forced regeneration, and claimed to have good efficiency with regard to nanoparticles. Their mechanical durability has been demonstrated through a series of applications in cars and trucks. In addition, the trap does not require any additional ash removal or maintenance, which significantly saves on cost. PM Metalit\(^\text{®}\) systems have been applied to production vehicles in Europe for various OEM and aftermarket applications\(^\text{20}\). However, the open filter concept is regarded controversially by some experts in the field. This is due to the possibility of the exhaust flow completely by-passing the filtering fleece material if the accumulated soot increases. If this is the case it is expected that the PM reduction performance is only marginally better than that of a flow-through Diesel oxidation catalyst.

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\(^{19}\) http://www.emitec.com/

J. Eberspaecher GmbH & Co. KG has introduced a metal-based diesel particulate filter that features an easy fabrication. The system is based on a sintered metallic fiber fleece as filtering material. The filter set-up consists of a simple folded arrangement. In this folded configuration the entire filter structure can be set up without any welding. In addition the filter concept offers a mass flow adapted cross section of the channels leading to very compact filters with a low pressure drop. This encourages a homogeneous temperature profile within the structure which improves the uniformity of regeneration conditions throughout the structure and thereby reduces partial regenerations.\textsuperscript{17}

**Regeneration methods**

**On-Board Diesel Particulate Filter Regeneration**

As discussed in the previous sections, diesel particulate filters have proven to be very effective in the reduction of Diesel particulate emissions. The particles captured eventually increase the exhaust back-pressure, causing a gradual loss of useful power from the engine. As DPFs are integrated into the exhaust line i.e. not removable or disposable, they require frequent in-situ oxidation of the accumulated matter, a process called regeneration, to prevent unacceptable levels of exhaust back-pressure.

Diesel particulate matter, in the absence of a catalyst, thermally oxidizes (at practically useful rates) at temperatures of around 600°C and above.\textsuperscript{21} However, such temperatures are not generally available in the exhaust pipe during normal engine operation. Even at high engine load, e.g. during high speed driving or when ascending an incline, Diesel exhaust temperatures generally remain below 500 °C. Therefore, it is necessary to employ technical means to enable the regeneration of the filter. In practical terms, the space and complexity restrictions of road vehicles generally prohibit regeneration modalities such as back-pulsing of compressed air and so the basic mechanism almost invariably employed is the oxidation of the carbonaceous soot. Concerning this mechanism, the actual technical implementation needed to achieve regeneration conditions is very much dependent on the DPF material, the geometrical design and even the DPF location in the exhaust line relative to the engine. Thermal conditions are the primary factor while oxygen availability is usually a non-issue due to the high oxygen content (8% - 10%) of Diesel engine exhaust. A significant, if not the dominant, component of energy consumption (fuel penalty) associated with a vehicle-installed DPF is attributable to the regeneration process. There is no strictly defined minimum soot mass at which regeneration must be performed and, therefore, there is a broad scope for maximizing the efficiency of the process.

For this reason, numerous methods of regenerating DPFs (via soot oxidation) have been studied, developed and implemented over the years. The plethora of methods investigated could be subject to a number of classification schemes. Frequently, practitioners in the field, differentiate between non-catalytic (generally, thermal) and catalyst-assisted regeneration. While it often occurs that similar technical means are involved in both of the above categories, there is a salient difference in the

temperature required for the process. Further, the presence or absence of catalysts in the DPF has many implications for material type and microstructure, DPF structure and tolerance to impurities present in the fuel or in the lubrication oil.

Another a classification, more closely related to the regeneration technique / control, is the distinction between a) discontinuous regeneration (initiated when a certain soot load or back-pressure is reached) and b) continuous regeneration by which the soot load is maintained below a certain level by mechanisms that work over a significant range of exhaust conditions (typically, with catalytic assistance).

Non-catalytic (thermal) regeneration
Discontinuous regeneration (also called “active” regeneration in many cases) can be induced by either raising the temperature of the particulate matter indirectly (by raising the temperature of the exhaust gas or the filter), or directly (by surface or volumetric heating of the particulate matter itself). Some regeneration methods of this type are listed below.

External heating: Since some electrical supply is always available in vehicles, the use of an electric heater is an obvious method to raise the exhaust gas temperature. The prime concern is its high energy consumption, since the energy required by the heater puts an extra load on the vehicle’s electrical system. In general, pre-heaters are not attractive because they must heat up the entire exhaust gas stream and are therefore very energy inefficient. On the other hand, direct (electrical) heating of the filter substrate requires that the substrate is an electric conductor, working as a resistive heater itself, as is the case with sintered metal fiber filters. Such a technique requires that the filter substrate is cut into continuous strips and that the metallic substrate is integrated into a DPF system with the use of a high temperature non-conductive adhesive. At the time of writing, electrically heated filter substrates in DPFs for the main powertrain still remain in the product pre-development stage for on-board regeneration. Retrofit systems employing off-line regeneration do exist commercially for fleet operations such as delivery trucks, school buses, city buses and other municipal vehicles, especially in the North American market. Sintered metal DPFs with on-board regeneration have been recently introduced for Diesel APUs in the North American motor home and long haul truck markets.

Microwave heating: The main advantage of microwave heating is its capability to deposit energy directly into the diesel particulate collected throughout the volume of the filter. This would theoretically enable very low energy expenditure due to the miniscule thermal mass of the trapped particulates in a DPF (typically of order 5 – 10 g per litre). The main difficulties reported with regard to microwave regenerated filters are related to achieving a satisfactory control over the energy distribution. Within an enclosure such as a DPF canister, microwaves tend to create a standing wave pattern with regions of high and low intensity. Countermeasures for this problem are further hindered by the dynamic nature of the microwave pattern – as the soot deposits distribution changes so does the location of high/low intensity spots. As a result, the filters tend to show uneven regeneration patterns, incomplete regeneration, or excessive localised exothermal heat release leading to substrate damage. Nonetheless,

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due to the lucrative advantages seen in the possibility for direct volumetric soot heating, many studies have been performed concerning this method but there have been very few attempts of fitting a microwave filter system on a diesel vehicle. A recent attempt was made within the FP7 project TOP-EXPERT\(^{23}\) where the approach involved the formation of a high intensity microwave-induced plasma at a section of the exhaust line, thereby aiming to treat suspended Diesel particulate directly.

*Injection of combustibles (fuel):* This method can increase the exhaust gas temperature by combusting an additional quantity of fuel which can be injected in two different ways. One method is by using the fuel injection system of the diesel engine in the engine cylinder, where the fuel is introduced through late cycle injection (post-injection). Alternatively, the fuel is injected in the exhaust gas stream, upstream of an oxidation catalyst through an additional injection system (exhaust port post-injection). The injection and subsequent oxidation of fuel hydrocarbons via an oxidation catalyst, either placed upstream of the filter or as a coating on the DPF itself, releases chemical energy and raises the exhaust temperature, thus assisting in the particulate matter oxidation. Since both methods unavoidably involve heating the exhaust gas flow, they demand a prohibitive fuel penalty if not used in combination with catalytic assistance.

*Non-thermal plasma:* Research carried out in the late 1990’s showed that diesel particulates can be oxidized and particulate matter trapping devices can be regenerated by using non-thermal plasma\(^{24}\). More precisely, the diesel particulates can be effectively oxidized by some reactive species generated in plasma, such as oxygen and OH radicals or NO\(_2\). An important advantage of plasma is the potential to oxidize particulates at low exhaust temperatures. It has generally been found that the critical issue with this method is the requisite energy consumption and, therefore, the imposed fuel penalty. The requirement for having a high voltage power supply on board also poses certain disadvantages.

**Catalytically assisted regeneration**

Regeneration of diesel particulate filters with the aid of catalysts can occur at temperatures well below those needed for unassisted oxidation (as low as 300 °C approximately) because the catalysts can generate active species that react with the soot at a lower activation energy. There are two types of catalytic DPF regeneration assistance recognised: a) indirect soot oxidation via species that can persist in the exhaust, such as NO\(_2\), and b) direct soot oxidation by catalysts that must be in “contact” with the soot. Indirect soot oxidation requires that the prevailing exhaust conditions provide appropriate temperatures in the area of 250°C – 350 °C for sufficient periods of time and sufficient NO\(_x\) emissions relative to the soot emission rate of the engine. Under such conditions – often available in older engines - DPF regeneration can even occur on a semi-continuous basis, potentially without active measures. However, nowadays the needed conditions are restricted niche applications due to higher engine efficiency (hence, lower temperatures) and lower / inadequate engine-out NO\(_x\) emissions levels. Even though active regeneration is the main focus of DPF management development, energy efficiency can be


improved by the catalyst too. Therefore, there has been extensive research focused on all related technologies in the past 20 years, with some activity remaining nowadays for direct soot oxidation catalysts.

The most significant implementations of indirect and direct catalytic soot oxidation assistance are: catalyst through a fuel-additive, catalyst coated DPF and the NO\(_x\)-assisted regeneration also known as “CRT”.

**Fuel additives** are usually blended into the fuel and are also called fuel-borne catalysts. Numerous metal additives (like organometallic compounds of cerium, iron, also Pt/Fe mixtures, sodium and lithium) have been employed, in combination with an uncoated filter wall-flow. The fuel-borne catalyst particles are usually of smaller size than those observed in catalyst-coated filters due to the low concentration of additive and high dispersion of the catalyst during its formation in the combustion cylinder. The fact that soot and catalyst formation is collocated means there is better contact between the catalyst and the carbonaceous particles (in fact, the smaller catalyst particles are dispersed within the soot particles). Many developments in fuel borne catalysts have been achieved by RHODIA which has equipped three million passenger cars in Europe with the Eolys\textsuperscript{TM} additive, without any recall\textsuperscript{25}. Disadvantages of these systems with fuel additives are: first, the need of an extra tank and a metering system on the vehicle to supply the additives into the fuel and second the accumulation in the DPF of the converted additives in form of ash. In fact, this aspect has been the main driving force for the development and commercial prevalence of asymmetric cell honeycomb DPFs discussed in chapter 2.1.

**NO\(_2\) assisted oxidation**: A very interesting design that uses the fact that NO\(_2\) can oxidise soot even at temperatures below 400 °C, is the continuously regenerated trap (CRT) originally developed by Johnson Matthey Plc. It consists of a wall flow monolith which is located downstream of the diesel oxidation catalyst which is called the pre-oxidizer. The oxidation catalyst generally converts 90% of CO and hydrocarbons present to CO\(_2\), and a temperature dependent fraction (typically 20% - 50%) of the NO to NO\(_2\). Further downstream in the DPF the particles are captured and gradually oxidized by the NO\(_2\). This design\textsuperscript{26} has many advantages such as e.g. its flexibility, and the ability of continuous regeneration over a temperature range of 200 - 450\(^\circ\)C. Some disadvantages about this system concern its dependence on a certain favourable NO\(_2\)/soot ratio in the exhaust stream and the shift of the tailpipe exhaust NO\(_x\) composition towards NO\(_2\) (known as NO\(_2\) slip). A more recent version of this system is a four-way emission control technology, the SCRT emission control system, which combines a two-stage CRT particulate filter with a selective catalytic reduction (SCR) catalyst, as shown in Figure 6. The SCR catalyst reduces NO\(_x\) by 60% to 80% through reactions with urea, which is injected upstream of the catalyst. The


two-stage particulate filter provides an over 85% PM emission reduction, as well as a reduction in CO and HC emissions. Such systems have been used for heavy-duty retrofit applications\textsuperscript{27}.

A variant of the CRT concept, related to catalytic DPF regeneration, is to coat the oxidation catalyst in the DPF wall itself. This arrangement is known, from detailed analysis\textsuperscript{28}, to allow the NO\textsubscript{x} effect to be multiplied due to the proximity of soot with the NO $\rightarrow$ NO\textsubscript{2} turnover sites. This can occur because the filtration flow through the wall is generally slow enough to allow the NO\textsubscript{2} produced in the oxidative coating in the porous wall to diffuse back to the soot layer. This degree of NO-turnover is heavily dependent on exhaust conditions and deposited soot mass, potentially reaching several times the molar flow rate of NO\textsubscript{x} into the DPF, e.g. at 350 °C and conditions of filtration flow velocity in the range of 2 – 4 cm/s, each NO\textsubscript{x} molecule entering the DPF may in effect react as many as 5 to 8 times with the soot before passing through the DPF. The drawbacks of collocating an oxidation catalyst with the filter wall include: a) compromises in DPF wall microstructure design for compatibility with coating integration, b) the danger for deterioration of pressure drop or filtration performance due to coating process fault/variability and c) a shift toward NO\textsubscript{2} emission, even more intensely than the DOC based system, downstream of a standalone DPF. Therefore, the DPF with an integrated oxidation catalyst coating is best combined with a downstream SCR converter.

Figure 6. Cut-away view of the SCRT\textsuperscript{29}.


\textsuperscript{29} http://www.matthey.com/
**Catalytic filter coatings:** Catalysed particulate filters (CPFs) were developed in the early 1980's, by coating the porous walls of a DPF monolith with an active catalyst. Various catalyst systems used for diesel filters utilize noble metals, base metals, as well as mixtures of those two. Platinum is the most active and the most commonly used noble metal, but also palladium is applied, while base metal coatings are relying on oxides of cerium/zirconium catalysts, usually combined. Catalysed filters in their pure, passive form rely on the exhaust gas temperature, and the use of the catalyst has been shown to reduce the soot oxidation temperature.

Nowadays, catalytic DPF development paths have moved beyond the limits of passive (CRT) behaviour (such as the CRT variant described in the previous section) and currently the trend is focusing on integrated management of the DPF over its entire scope of operating modes (e.g. loading, regeneration, ash-induced aging). In this sense new concepts of multifunctional catalytic filters have been investigated with the potential to:

- exhibit some oxidation activity under moderate exhaust temperature, to prolong the intervals between forced regenerations as much as possible, to exploit direct (i.e. through oxygen transfer) as well as indirect (through NO\(_2\) generation) soot oxidation
- exhibit reduced soot ignition temperatures compared to filters without catalyzed walls allowing energy savings during regeneration
- be tolerant to ash accumulation

The key parameter that affects the filter performance with respect to its regeneration, in the case of direct (oxygen transfer) soot catalysts, is the degree of contact between the catalyst and the collected soot. APTL works extensively in research activity concerning advanced catalyst synthesis and coating. A number of soot catalyst formulations have been developed and coated on DPFs via the so-called Aerosol-based Synthesis and Deposition. With this method the synthesis step and the attachment of the catalyst particles on the filter wall, are combined in one step. The catalyst precursor solution is nebulized and the microdroplets pass through a heated tube reactor to form sub-micron solid particles. These can deposit directly on the filter substrate that is placed in the heated zone or can be collected and resuspended in a carrier liquid for mainstream slurry coating application. Results using the direct aerosol deposition method have shown that the soot/catalyst contact can be improved compared to a conventional coating method, as evidenced by the sustained reaction rate shown in Figure 7.

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31 Ibid.
Photocatalysis: The photocatalyst-plasma-honeycomb (PPH) filter system introduced by Neophotech Inc and GM Daewoo Auto & Technology\textsuperscript{36,37} in 2002 is one of the more noteworthy attempts to find non-thermal and energetically milder means for Diesel soot abatement. The PPH system uses titania based photocatalysis for the oxidation reactions, not only for soot burning but for carbon monoxide and hydrocarbons treatment as well. The necessary photonic energy for activating the photocatalysts is supplied through plasma discharge occurring within the monolith channels and it has been shown that the method can regenerate the DPF continuously\textsuperscript{38}. The demonstrated power consumption (circa 200 Watt for treatment of exhaust from a 2.9 litre Diesel engine) is potentially compatible with continuous operation, however, the particulate emissions reduction provided by the proposed devices has not been rigorously quantified in the available literature and follow-on applications of the technology have not been seen. It is also not apparent if the photocatalytic concept could tolerate a temporary cessation of the soot catalysis function since the accumulation of a soot layer could optically decouple the catalyst surface from the UV light or could hinder the generation of plasma due to its conductivity. The prospect of a continuous cleaning function also leads to the concern for meeting filtration efficiency requirements since there will be no soot layer formation, a necessary condition nowadays for most systems to comply with particle emissions limits.

“Shore Power” Regeneration

Due to the prevalence of Diesel powertrain in commercial vehicles, there is very often the possibility to manage the DPF system on a fleet management framework in which the vehicle returns to a fleet base at more or less regular intervals. This allows the adoption of DPF management schemes in a way that the regeneration equipment, power source and control are handled at the fleet depot, freeing the vehicle design from having to incorporate a DPF management system. The Donaldson semi-active DPF system\(^{39}\) is an example of a heavy duty DPF system that is electrically regenerated off-line i.e. suitable for fleet operations such as an urban bus transport system. In this case the heater is a separate electrical element located upstream of a wall-flow silicon carbide DPF monolith, used in conjunction with an off-vehicle air pump, i.e. using the so-called “shore power regeneration”. The energy penalty associated with heating the engine exhaust (substantial even during engine idling) is avoided by performing the regeneration with the engine switched off and having an auxiliary device forcing a small amount of flow through the DPF to prevent overheating and maintain a adequate supply of oxygen.

Many heavy duty fleet operations, such as public school buses\(^{40}\), have served as applications for retrofit systems using shore power regeneration. Makers/integrators of such systems have included Cleaire (USA), Engine Control Systems (USA) and Donaldson (USA). Separate electrical heating elements have been utilized also for on-board off-line regeneration of DPFs fitted to smaller engines\(^{41}\), with verification of the regeneration effectiveness. Most of these systems employ ceramic wall-flow filter monoliths and therefore require periodic “de-ashing” (ash removal) as part of their regular maintenance\(^{42}\). The energy savings, from avoiding on-line regeneration fuel penalty, and the relative simplicity of the concept makes it suitable for certain OEM applications.

In general, shore power systems can be applicable to hybrid commercial vehicles which return with sufficient frequency to the fleet base such that the DPF back-pressure is maintained at acceptable levels during operation. However, it is unlikely that the heating elements of such DPF regeneration systems will be at all usable during vehicle operation since the exhaust/DPF heater is sized for attaining regeneration temperatures under near-zero exhaust flow conditions. Even with appropriate sizing of the heating system, it is expected that the power requirements will be prohibitive even under engine idling conditions. Therefore, for hybrid vehicles, such electrical regeneration modalities are unlikely to offer efficiency gains related to advanced utilization of regenerative breaking (peak-shaving) energy, potentially available and that may be otherwise lost due to traction battery lifetime considerations.

Off-board regeneration

The management of the DPF by its removal from the engine / vehicle is another possibility which allows direct installation of the DPF on the exhaust line with no requirement for additional management.


\(^{41}\) http://news.pickuptrucks.com, 10\(^{th}\) June 2010.

\(^{42}\) Cleaire Advanced Emission Controls, LLC, Electric Diesel Particulate Filter Demonstration for the California Air Resources Board, 31\(^{st}\) March 2006.
facilities. However, for medium to heavy duty vehicles this is considered impractical from logistics and customer acceptance considerations and so is not really considered a viable candidate for HCV’s in general. Furthermore, as with on-board shore power concepts, off-board regeneration provides no scope for advantageous integration with the hybrid power net and use of potentially available peak-shaving of recuperated energy.

**Unconventional DPF concepts**

There are a number of unconventional (with respect to the established practice in automotive and heavy-duty Diesel emissions control) DPF concepts or methods of operation which deserve to be mentioned in this review, for reasons of completeness and of potential relevance with the electrification effort of WP2400.

**Partial filters**

In many heavy duty applications, especially of the retrofit type, particulate abatement systems are required for upgrading of otherwise non-compliant heavy duty engines. For such upgrading scenarios, partial filters (such as the Emitech PM-KAT®) have been considered, with roughly 50% reduction in particulate emissions being sufficient for an already nearly compliant engine. However, there is diminishing scope for applicability of such “open filter” systems as the sole/primary Diesel particulate abatement measure, as emissions limits are getting more stringent, especially with forthcoming particle number requirements.

**Electrostatic precipitator soot trap**

One concept which differs significantly from the mainstream mechanical filtration systems is the electrically operated partial or open DPF, such as the Per-Tec PowerTrap® which implemented an electrostatic principle for the soot capture. Unfortunately, the commercial availability of this novel electrical DPF system seems to have stopped. A related principle, electrostatic precipitation (promoting soot particle agglomeration through electrostatic means), has been proposed many years before the onset of widespread DPF commercialization. It claims having low and constant pressure drop (silencer-like behaviour) and independence of the exhaust flow temperature for DPF operation (as opposed to catalytic CRT systems). The basis of this system is the electrostatically induced agglomeration of the particles to bring average particle size above 1 μm, i.e. a size range where the particles are separable from the exhaust flow inertially e.g. by a cyclone. Filtration efficiencies up to 90% have been

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claimed in the electrostatic soot precipitator systems\textsuperscript{49,50}. Such systems could leverage some facilities from the electrical power available on the HCV platform, although the concept claims to be very energy efficient (they require high voltages but not high power per se). However, apart from a recent reincarnation of the concept in combination with porous metal foam\textsuperscript{51}, no further significant pursuit of precipitator based concepts has been seen. These methods also are sensitive to some exhaust and soot conditions (initial soot particle charge distribution, exhaust temperature). Although relevant to the electrification targets of WP2400, on the whole, the electrostatic precipitator concept is considered excessively risky as a candidate both on the grounds of sensitivity to exhaust/soot conditions as well as the tighter (Euro6) emissions limits that are coming into effect.

**DPF management strategies employing model based control and partial regeneration**

A recurring theme in DPF management strategy is that of model based control of the DPF regeneration. Additionally, some concepts aim to leverage the higher efficiency of regeneration available at higher soot load states. The DPF back pressure is almost invariably used as the main criterion for determining regeneration frequency and/or duration of post-injection. In many instances of DPF systems, however, a model-based estimation of soot loading state, hosted on the ECU, is also included as part of the control algorithm. Examples of such advanced strategies for controlling DPF regeneration were developed during the European project IMITEC (IST-2001-34874). The concept of a virtual sensor was introduced, which monitors the amount of soot collected inside the filters and gives information for the initiation (and cessation) of the regeneration process\textsuperscript{52}. These techniques can provide substantial optimisation of the regeneration process, saving fuel, however they are challenged by effects due to non-uniformity in the soot load distribution within the DPF. Therefore, basic forms of model based regeneration control are employed but always in combination with exhaust back-pressure or other history-dependent criteria as a back-up regeneration stimulus.

\textsuperscript{50} SAE Paper 860009, March 1986.
DPF Technologies Comparison

Comparison parameters / technical and economic aspects considered

In order to design diesel particulate filters or to select the appropriate technology for a given application, the following assessment criteria are generally considered:

Performance

- Filtration efficiency (on a mass and number basis, size specific as well as total mass/number)
- Pressure drop behaviour (in the clean state and during loading, regeneration limit, safety limit)
- Regeneration performance and compatibility with specific regeneration technologies (i.e. electrical regeneration)
- Ash storage capacity / tolerance to ash accumulation

Reliability / Durability

- Chemical durability in the exhaust environment (including ash particles and filter material interactions)
- Mechanical durability
- Resistance to thermal shock (for safety against uncontrolled regeneration or non-uniformities in soot load)
- Compatibility with washcoats/catalysts

Cost

- Capital cost (incl. system integration/optimization)
- Operating cost (including fuel penalty)
- Maintenance cost

In the context of HCV SP2000 where the electrification of the DPF system is considered in parallel with similar effort for other powertrain auxiliaries, the compatibility of each DPF technology with electrical power integration must also be considered.

It should be noted that the basis for any technology comparison is a function of the specific conditions that each application presents. The basis of the comparison presented here is not restricted to the criteria relevant only to the prototype hardware build and test requirements of WP2400 but instead aims to be a more generally applicable assessment for the selection of a DPF system for Diesel hybrid commercial vehicles for which a fully electrical management of the DPF is specified.
Discussion of prevalent technologies

**DPF technologies based on extruded porous ceramics**

The ceramic wall-flow filter is the most common type of DPF mainly due to its high filtration area (> 1 m² per litre of trap volume has been achieved with 320 cpsi honeycomb monoliths) and its high filtration efficiency (initial efficiencies generally above 60%, loaded efficiencies > 99% are obtained). Among the various possible materials, SiC based materials are favoured primarily due to their high maximum operating temperatures and the increased mechanical strength. The melting point of SiC is 2730°C (decomposition point) compared to 1470°C and 1850°C for cordierite and mullite (dependent on their composition). Of course the sintering temperature of the ash particles is an equally important parameter. Temperatures as low as 900°C can cause significant sintering of the ash particles on the filter substrate which may lead to serious deterioration of the filter’s long term durability. Thus, the maximum operating filter temperature may, in fact, be limited by the interaction of the ash particles with the ceramic filter material. SiC filters are characterized by uniform open-pore networks (i.e. relatively narrow distribution of pore size) and thus, higher permeability leading to lower pressure drop. This is due to the fact that SiC DPFs are invariably made from a powder precursor which is either sintered or bonded to form a porous wall. The cordierite, aluminium titanate (AT) and mullite porous filter wall is the result of a reaction-based process (physical components, such as pore former may be included).

Although the majority of the ceramic filters attain excellent filtration efficiencies enabling compliance with future emission standards, a test campaign performed in 2006 at APTL demonstrated that the best filtration efficiency was achieved using SiC filters.

SiC filters possess higher thermal mass than the other candidates. This is an advantage in case uncontrolled filter regeneration is a concern since the DPF wall can provide some buffering of exotherms. However, it is a disadvantage under normal regeneration, as more energy is necessary to heat up the filter to the desired temperature.

The thermal conductivity of SiC is one order of magnitude higher than that of its competitors. This, again, is an advantage as it reduces the magnitude of temperature gradients that can result from hot spots. However, the higher the thermal conductivity also enhances thermal losses hence again making regeneration more difficult. On the contrary, especially cordierite can offer faster heat up due to low thermal mass and fewer thermal losses (at the expense of not being robust to thermal extremes). Another drawback in material properties is that SiC demonstrates lower thermal shock resistance than its competitors mainly due to its fivefold higher thermal expansion coefficient and high elastic modulus, which means that for a certain temperature gradient, the thermal stresses induced in the SiC material will be more intense than would be the case for cordierite, mullite and AT. The latter three DPF materials all exhibit superior resistance to failure under high thermal gradients. The development of the AT material for DPF application, as introduced by CORNING in its Duratrap filters, was motivated by the prospect of very good thermal shock properties (same as cordierite) while keeping an equal or higher

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mechanical strength. The low thermal shock resistance of SiC filters is tackled by the technique of filter segmentation, that is, SiC DPFs are assembled from several longitudinal segments, with the space among them filled with a bonding material. The interstitial bonding material is able to relieve the thermal stresses, that could cause DPF failure, by its lower elastic modulus and mechanical strength, i.e. the bonding material may be strained or cracked but the SiC segments remain intact and the integrity of the DPF is maintained by the compression under which it is canned.

All ceramic materials (mostly oxides) used for filter manufacturing can withstand the oxidizing conditions of the diesel engine exhaust. In the case of non-oxide materials like SiC, a protective oxide layer is built at the surface of the materials. Attention should be paid on the ceramic – metal oxide (originating from the metal ash particles) interactions. The melting point of the ceramic material can be locally lowered due to the formation of eutectics with the metal oxides. Local stresses can also be present due to solid state reactions between ash particles and the ceramic material. Filter thermal control needs to be carefully applied to avoid elevated temperatures where such phenomena may occur.

All ceramic materials in mainstream DPF use exhibit good compatibility with catalysts and washcoats. The catalyst particles used in DPF applications are in nanometric size range close to the size of the soot particles to maximize the soot/catalyst contact. Careful distribution of the catalytic nanoparticles should take place in order to avoid lowering the thermal shock resistance of the substrate material. This is particularly true for materials with a high degree of internal micro-cracking like the aluminium titanate (AT) material, because in this material local increase of the thermal expansion coefficient could lead to filter damaging. Special treatment methods have to be applied before the application of the washcoat and catalyst to the AT material.

Finally, SiC based DPFs tend to be more expensive than others due to the higher raw material costs and the higher process temperatures involved. Naturally, the relative costs are subject to production volumes and thus, relative prices can vary over time. The cost of SiC DPF material has approached that of cordierite in recent years. On the other hand, the superior thermal shock resilience of the AT material allows for monolithic extrudates to be employed even for single heavy-duty size DPFs, thus simplifying manufacturing and significantly reducing cost for such large DPF.

Ceramic DPF materials generally must be integrated to the exhaust line through canning with packing mats and peripheral compression. This requires DPF housings which have round or oval cross-sections and so ceramic materials may present some degree of incompatibility with the exhaust box housings favoured for heavy duty applications in that some dead volume in the exhaust system may be unavoidable.

With respect to electrification, there have been attempt to apply electric self-heating to SiC which is in fact a semiconductor. The issues that arise with SiC as a heating element are the problematic interfacing to the electrical connections (ceramic-to-metal at temperatures >600 °C), the relatively high voltages needed (not directly compatible with 24 V or 48 V power nets) and the negative resistivity coefficient of the semiconductor material with temperature i.e. the resistivity drops as the material heats up, necessitating special voltage control provisions from the power supply for safety.
More generally, the electrification of ceramic DPF materials (for on-board on-line regeneration) requires the use of separate heating elements and will generally suffer from the fuel penalty arising from the energy expenditure to heat up part or all of the exhaust.

**DPF technologies based on metallic materials**

Metallic DPF materials can be based on a granular precursor or a fibre precursor. Among the examples of such materials seen in Diesel emissions control, some degree of sintering of the precursors is invariable employed to provide a cohesive / durable filter wall.

The main advantages of **sintered metal** filters are their mechanical durability and their resistance to thermal shock. Another major advantage, especially in hybrid vehicle applications, is that an electrical current can be applied, directly heating-up the filter material (at least in certain filter configurations), leading to significantly better fuel economy related to filter regeneration. In contrast with semiconductor ceramics such as SiC, sintered metal DPF materials can be integrated with electrode connections relatively easily, their resistivity is generally compatible with 24 V or 48 V power nets, and they exhibit increasing resistivity with temperature, the latter characteristic offering an additional degree of thermal safety.

The fine-grained / thin fiber components of sintered metal materials typically consist of Fe-Cr-Al or Fe-Cr-Ni alloys which are formulations developed for high temperatures and aggressive environments. In these alloys, a self-forming \( \text{Cr}_2\text{O}_3 \) layer protects the filter surface but decomposes above 900°C. The aluminium (or nickel) oxide components continue to protect the filter surface up to significantly higher temperatures. Nevertheless, chemical stability is always an important issue that has to be taken into account concerning the determination of the useable lifetime of the metal DPF. Increasing the aluminium content usually extends the filter durability, but also increases the material brittleness. The available materials (granular and fibrous) in this category have by now accumulated sufficient experience in Diesel exhaust applications so to make further optimisation of the alloy composition redundant.

The compatibility of traditional catalysts/washcoats is, however, an issue for metal filters although the thermal (not catalytically assisted) regeneration efficiency that has been demonstrated in some systems makes this a less important factor.\(^{54}\) Additionally, increasing the filtration area of the DPF is a more difficult task for metal filters. The manufacturing of complex and difficult arrangements has to be considered in order to impose an increased filtration area, although filtration areas up to 0.9 m\(^2\)/L have been reported\(^{55}\) with some materials.

In comparison to ceramic filters, the metallic materials that have been considered for DPF application have generally demonstrated lower filtration efficiency. Sintered metal granular materials have a porosity of around 60% while metal fleece materials have a porosity of 80% - 90% compared to 40% - 50% for the ceramic materials. Porous wall structures with sintered metal particles on a wire mesh

\(^{54}\) Hi-CEPs Project, "Highly Integrated Combustion Electric Propulsion System," contract no. TIP5-CT-2006-031373.

support have demonstrated 80% - 90% filtration efficiency\textsuperscript{56}. However, this was achieved at the expense of increased filter weight and, consequently, thermal mass. Structures involving metal fibre felts or fleeces are lighter but usually come with somewhat lower initial filtration efficiency (20% - 40%) during the clean state of the filter. When soot is trapped by the filter material, filtration efficiency increases beyond 99% as with all filter wall structures that sustain the formation of a soot deposit layer. At the time a soot layer is established on the filter material the filter pressure drop evolves linearly with the amount of soot accumulated on the filter (for a constant exhaust mass flow), i.e. these materials exhibit comparable filtration behaviour with ceramic materials after some soot loading.

Metallic fleece materials have been also incorporated in some, so-called, open filter types where only partial filtration of the flow occurs. In general, these partial flow metal filters have far lower efficiencies than the ones aforementioned and therefore, they will most likely be inadequate to overcome future particle emission limits for most applications. Therefore, only full flow (or so-called “closed”) implementations of sintered metal filters are considered for the current context.

Granular sintered metal filters exhibit similar but generally better permeability than most of the ceramic DPF materials. On the other hand, the permeability of metal fleece filters is orders of magnitude higher than that of ceramic filters. Therefore, they exhibit negligible pressure drop when they are operated in clean state. Once the soot cake has been formed on the filter structure, they typically show very high pressure drop slopes. This occurs because of the relative small filtration area that can be feasibly incorporated in such filters, for a given device volume constraint. On the other hand, granular sintered metal (powder and mesh) filters can have similar volumetric densities of filtration area and so have similar pressure drop behaviour with wall flow monoliths.

In considering long term operation, however, metal filters have an important advantage in the ash tolerance they display. Due to the topology of the spaces with the metal DPFs, ash accumulation does not generally inhibit the operation of the metal filter - in fact, there can be an improvement of filtration efficiency - whereas for the ceramic wall-flow monoliths it decreases the actual filtration area throughout the life-time of the filter and therefore leads to increased pressure drop near the end of the filter life.

Finally, the construction of metal filters is on average more expensive than that of ceramic wall-flow monoliths. Nevertheless, it has to be taken into account that the two competing technologies are not at the same state of development. R&D effort still needs to be done on some aspects of metal filters for mainstream adoption for vehicle power train exhaust after-treatment.

**DPF technologies based on ceramic fibers**

Advantages of ceramic fiber filters include their very good thermal stability (low coefficients of thermal conductivity and expansion), tolerance to ash particle accumulation (no clogging with ash particles, like metal filters), noise attenuation properties and the fact that they show very little risk of clogging with soot particles. Ceramic fiber materials (glass, leached silica, fused silica) demonstrate incompatibility to

\textsuperscript{56} EU funded project: Coated Sintered Metal Trap (COMET), Contract: G3RD-CT-2002-00811.
the known washcoats/catalysts, at least with the commonly practiced coating techniques. These filters are comprised of a woven or mechanically wound yarn layer over a cylindrical filter cartridge. The woven types are prone to channelling if not knit uniformly: that is, the exhaust gas flows through pathways of lower fiber density across the yarn layer, which leads to reduced filtration efficiency. Sintered ash particles may also bind fibers together, which then are subject to vibrational failures. The dominant filtration mechanism in ceramic fiber filters is the deep bed filtration, which shows the best efficiency. Nevertheless, most applications demonstrated low filtration efficiencies without any special advantage regarding the filter pressure drop. This is their main drawback. Moreover, they tend to occupy more space in the exhaust and may emit secondary emissions in case of fiber breakage. Finally, they do not present any cost advantage compared to ceramic wall-flow filters. However, a possible advantage, especially for hybrid vehicle integration, could be that they more easily facilitate electrical regeneration. The difference to the metal fiber filters is that the filtration medium itself cannot be electrically heated. Instead the fiber support cartridge, present already in the DPF construction, can assume a dual role and be used as a heating element. This arrangement, of course, is a less direct deposition of thermal energy to the soot layer that must be burned but it is the main available method since the close-coupled incorporation of heating wire into the ceramic fibers is known to lead to overheating and localised failure of the filter material. Because of this constraint, smaller energy densities are obtained and longer heating intervals / more energy are needed for achieving DPF regeneration.

DPF technologies based on (metal/ceramic) foam microstructure

Ceramic foam filters can be made out of every available high-temperature ceramic material (e.g. SiC, cordierite, mullite) that can form a slurry precursor and, therefore, the foam microstructure can be combined with the advantages and disadvantages of each material. On the other hand, foam filter structures must always be tested extensively concerning their mechanical durability. Metal foams made from sintered metal powder generally have better mechanical behaviour due to the elasticity and plasticity inherent in metals.

Foam filters can have a wide range of pore densities: very low (10 pores per inch, ppi) up to very high (50 ppi) ones. As seen in research projects, such as STYFF-DEXA\(^7\), the low pore density foams can exhibit low pressure drop but suffer from inadequate filtration efficiency. Foams with higher pore density can reach moderate filtration efficiencies at the expense of very high pressure drop. This is mainly a consequence of the difficulties of shaping foam material for high filtration areas within the compactness required by road vehicles. Therefore, in practice, filtration efficiencies higher than 50\% cannot be obtained at acceptable pressure drop values or DPF size and foam materials generally do not exhibit the formation of a soot deposit cake. On the other hand, especially ceramic foams have properties that make them very suitable for advanced catalytic converter substrates, in which case they also provide a partial soot filtration function and a uniform flow distribution (useful when followed downstream by other honeycomb after-treatment devices). That is the case because they do not restrict the flow in the radial directions as extruded honeycombs do. These properties were exploited by Arvin Meritor in the so-called

\(^7\) Simulation Tool for Dynamic Flow Analysis in Foam Filters (STYFF-DEXA), Project contract G3RD-CT-2002-00785.
“Soot Capacitor” device\textsuperscript{58,59} essentially a DOC employing an open-cell foam substrate. Such a concept allows some downsizing of the downstream DPF since a portion of the soot emissions is captured by the ceramic foam DOC and oxidized passively by the NO\textsubscript{2} which is produced by the coating of the oxidation catalyst. Metallic foams do not have the same compatibility with catalyst coatings but can attain higher cell densities i.e. better partial soot capture function as well as flow distribution. Therefore, ceramic foams (and metallic foams, to a lesser extent) can remain under consideration for auxiliary functions (soot reduction, oxidation catalyst, flow distribution) in conjunction with a downstream DPF.

**Ranking of Existing DPF technologies**

In the following tables, several DPF technologies are compared with respect to their performance, durability/reliability and cost. The rankings in each of these categories are presented in Table 2, Table 3 and Table 4, respectively.

The definitions of the symbols used as ranking indicators are as follows:

- × poor / unacceptable
- ✓ fair / acceptable
- ★ good
- ★★ excellent

\textsuperscript{58} http://www.dieselnet.com/update.php?issue=200608.
Table 2. Comparison of different DPF technologies based on their performance.

<table>
<thead>
<tr>
<th>Performance metric:</th>
<th>Filtration efficiency</th>
<th>Pressure drop / compactness</th>
<th>Regeneration</th>
<th>Ash tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic wall-flow filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon carbide (SiC)</td>
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<td>Sintered metal particles on wire mesh</td>
<td>✓</td>
<td>✓</td>
<td>⚫</td>
<td>⚫</td>
</tr>
<tr>
<td>Sintered metal fiber felt/fleece</td>
<td>✓</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
</tr>
<tr>
<td>Metal foam (partial filter) (partial filter)</td>
<td>×</td>
<td>✓</td>
<td>⚫</td>
<td>⚫</td>
</tr>
<tr>
<td>Ceramic fiber filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cartridges</td>
<td>×</td>
<td>✓</td>
<td>⚫</td>
<td>⚫</td>
</tr>
<tr>
<td>Assembly of wafers in cartridges / 50 p.p.i.</td>
<td>×</td>
<td>✓</td>
<td>⚫</td>
<td>⚫</td>
</tr>
<tr>
<td>Ceramic foam filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cylindrical wafers (short monolith) soot capacitor</td>
<td>×</td>
<td>✓</td>
<td>⚫</td>
<td>⚫</td>
</tr>
</tbody>
</table>
Table 3. Comparison of DPF technologies based on their durability.

<table>
<thead>
<tr>
<th>Durability/reliability metric:</th>
<th>Mechanical</th>
<th>Chemical</th>
<th>Thermal Shock</th>
<th>Catalyst compatibility (adhesion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic wall-flow filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiC</td>
<td>★★★</td>
<td>★★★</td>
<td>✔</td>
<td>★★★</td>
</tr>
<tr>
<td>Cordierite</td>
<td>★★</td>
<td>★★★</td>
<td>★★</td>
<td>★★★</td>
</tr>
<tr>
<td>Mullite</td>
<td>★★</td>
<td>★★★</td>
<td>★★</td>
<td>★★★</td>
</tr>
<tr>
<td>AT</td>
<td>★★★</td>
<td>★★★</td>
<td>★★</td>
<td>★★</td>
</tr>
<tr>
<td>Metal filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sintered metal particles on a wire mesh</td>
<td>★★★</td>
<td>✔</td>
<td>★★★</td>
<td>✔</td>
</tr>
<tr>
<td>Sintered metal felt/fleece</td>
<td>★★★</td>
<td>✔</td>
<td>★★★</td>
<td>✔</td>
</tr>
<tr>
<td>Sintered metal foam (partial filters)</td>
<td>★★★</td>
<td>✔</td>
<td>★★★</td>
<td>✔</td>
</tr>
<tr>
<td>Ceramic fiber filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cartridges</td>
<td>×</td>
<td>★★</td>
<td>★★★</td>
<td>×</td>
</tr>
<tr>
<td>Ceramic foam filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly of wafers in cartridges / 50 p.p.i.</td>
<td>✔</td>
<td>★★★</td>
<td>★★</td>
<td>★★★</td>
</tr>
<tr>
<td>Cylindrical wafers (short monolith) soot capacitor</td>
<td>✔</td>
<td>★★★</td>
<td>✔</td>
<td>★★★</td>
</tr>
</tbody>
</table>
Table 4. Comparison of DPF technologies on the basis of costs.

<table>
<thead>
<tr>
<th>Cost metric:</th>
<th>Capital</th>
<th>Operating</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extruded ceramic (wall-flow)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiC</td>
<td>★★</td>
<td>★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>Cordierite</td>
<td>★★★</td>
<td>★★</td>
<td>★★★</td>
</tr>
<tr>
<td>Mullite</td>
<td>★★</td>
<td>★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>AT</td>
<td>★★</td>
<td>★★</td>
<td>★★★★</td>
</tr>
<tr>
<td><strong>Metallic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sintered metal particles on a wire mesh</td>
<td>✓</td>
<td>★★</td>
<td>★★</td>
</tr>
<tr>
<td>Sintered metal felt/fleece</td>
<td>✓</td>
<td>★★★</td>
<td>★★</td>
</tr>
<tr>
<td>Sintered metal foam (partial filters)</td>
<td>✓</td>
<td>★★</td>
<td>★★</td>
</tr>
<tr>
<td><strong>Ceramic fiber</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cartridges</td>
<td>✓</td>
<td>★★</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Ceramic foam</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly of wafers in cartridges / 50 p.p.i.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Cylindrical wafers (short monolith) soot capacitor</td>
<td>✓</td>
<td>★★</td>
<td>★★</td>
</tr>
</tbody>
</table>
Requirements for exhaust gas after-treatment for diesel hybrids

Due to the progress in Diesel combustion systems, it is possible that some parts of future emission standards could be fulfilled without after-treatment – despite the higher average engine loads caused by the hybridization – especially if extreme load peaks of the ICE are eliminated by e-motor boosting. However, in some markets there are already requirements for not-to-exceed emission limits also outside the legislative cycles and it is possible that this will be adopted more widely in the future. Continuous PM trap regeneration with CRT-effects is no longer as effective due to the low NOX-engine emissions achieved by the hybrid Diesel powertrain. Even with the much lower PM emissions due to the improvements in the combustion management, the missing CRT effect would require thermal trap regeneration, which causes higher fuel consumption. In the context of commercial vehicles, this thermal regeneration will need to be performed in predominantly (if not exclusively) urban driving conditions, raising further the risk for higher fuel penalty. Considering all this, it becomes clear that the selection of an after-treatment system for diesel hybrids is not a trivial task.

The technology selection carried out here considers only the PM filter system, weighing especially on electrically assisted systems, as required by WP2400, which would benefit from the high power electric facility available on the hybrid commercial vehicle and, thus, could lead to advantageous solutions in this application of Diesel exhaust after-treatment.

In order to propose a system for a diesel hybrid vehicle the following requirements are considered important:

- Raw engine out emission (gaseous pollutants and particulates)
- Emission targets of the internal combustion engine
- Emission targets during vehicle operation, considering the operation of both the diesel engine and the electric motor
- Exhaust gas conditions based on hybrid operating points (temperatures, flow rates) and prevailing driving conditions
- Acceptable exhaust backpressure (the effect on engine performance and fuel economy should be minimal)
- Available electrical energy and allowable power drain (and its scheduling) for regeneration
- The possibility to use the DPF as an advantageous power sink for peak shaving during intervals of regenerative breaking when the power exceeds the recommended peak charging rate of the battery pack
- Available space for DPF and power electronics installation
- Implementation cost compared to mainstream DPF systems.
Flexibility in DPF sizing and in regeneration frequency can be important for urban bus applications and could lead to route-specific after-treatment setups since the route characteristics have been identified as the primary determinant in particulate emissions\(^{60}\). Another aspect that needs to be considered is the urban driving conditions that are the mainstay of the target hybrid commercial vehicle applications. The fuel penalty for conventional (fuel post-injection) regeneration for exclusively urban driving can be a multiple of the fuel penalty achieved by vehicles with regular extra-urban driving intervals. In this context, electrification of the DPF regeneration does not concern only the separation of engine function (prevailing exhaust temperature) from auxiliary management, as is the case for other powertrain auxiliaries considered in the HCV project. DPF electrification may be a means for substantial energy savings for DPF management by enabling the targeted deposition of thermal energy to the soot that must be oxidised, something not possible with the mainstream method of fuel post-injection as the means of DPF management.

For the purposes of a technical comparison and selection of the electrified DPF technology to investigate in WP2400, the aforementioned factors are condensed into three main categories:

- a) potential efficiency gains from electrical regeneration,
- b) compatibility with the hybrid vehicle electrical facilities,
- c) implementation difficulty / cost.

A comparison based on these categories, using the same ranking indicators as in the previous section, is shown in Table 5 below. It is apparent that a number of viable candidates are potentially available, each with advantages and/or shortcomings in different areas. It is also apparent that the DPF concepts that embody a directly heatable substrate are considered the most promising for significant regeneration efficiency gains. Due to the electrification targets of the current project effort, these factors are given the most weight in the final comparison and selection, although this selection cannot be made independently from basic DPF technical factors (especially filtration efficiency) discussed in the previous section.

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\(^{60}\) Holmén B., Final Report to Connecticut Transit (CTTRANSIT) and Joint Highway Research Advisory Council (JHRAC) of the Connecticut Cooperative Highway Research Program (JHR 05-304), August 2005.
Table 5. Comparison of candidate electric DPF technologies.

<table>
<thead>
<tr>
<th>Performance metric:</th>
<th>Potential electrical regeneration efficiency</th>
<th>Compatibility with hybrid electrical facilities</th>
<th>Implementation difficulty / cost</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC substrate as resistance heater</td>
<td>★★★</td>
<td>✓</td>
<td>x</td>
<td>Direct contact of heated substrate and soot deposits. Cannot be directly powered by 24/48 V power nets. Special voltage control needed due to negative resistance temperature coefficient. Electrical interfacing to porous SiC elements difficult.</td>
</tr>
<tr>
<td>SiC / upstr. heater</td>
<td>x / ✓</td>
<td>x / ★★</td>
<td>★★★ / x</td>
<td>(Variants: a. direct integration / b. flow partitioning with valves.) Direct integration of upstream heater: energetically disadvantageous (lower fuel penalty by fuel post-injection) and excessive power level. Energetically acceptable with exhaust flow partitioning and valves but implementation suffers due to complexity and moving parts in the exhaust environment. Cordierite more suitable due to lower heat capacity and lower thermal conductivity.</td>
</tr>
<tr>
<td>Cordierite / heater</td>
<td>x / ★★</td>
<td>x / ★★</td>
<td>★★★ / x</td>
<td></td>
</tr>
<tr>
<td>Mullite / heater</td>
<td>x / ✓</td>
<td>x / ★★</td>
<td>★★★ / x</td>
<td></td>
</tr>
<tr>
<td>AT / heater</td>
<td>x / ✓</td>
<td>x / ★★</td>
<td>★★★ / x</td>
<td></td>
</tr>
<tr>
<td>Sintered metal powder on wire mesh</td>
<td>★★★</td>
<td>★★★</td>
<td>✓</td>
<td>Direct contact of heated substrate and soot deposits. Fibrous has lower thermal mass (faster heat-up) and better contact with soot than sintered metal powder. Modular design: voltage and power requirements can be adapted to any low voltage vehicle power net but DPF demands more construction effort. Controlled by simple switching circuits. Implementation of sintered powder into electrical modules less mature than fibrous.</td>
</tr>
<tr>
<td>Sintered metal micro-fiber felt / fleece</td>
<td>★★★</td>
<td>★★★</td>
<td>★★</td>
<td></td>
</tr>
<tr>
<td>Cartridges with resistance heater supports</td>
<td>✓</td>
<td>★★★</td>
<td>★★</td>
<td>Implementation as electrical DPF has been shown / more mature than others. Ceramic fiber durability limits electrical power intensity and prevents direct heating of substrate in contact with soot so smaller efficiency gain.</td>
</tr>
<tr>
<td>Electrostatic precipitator</td>
<td>★★★</td>
<td>✓</td>
<td>x</td>
<td>Very high voltage supply needed. Possible interference with vehicle electronics and safety concerns. Tolerance of regeneration process with exhaust conditions not fully known.</td>
</tr>
<tr>
<td>Microwaves + wall-flow (not SiC)</td>
<td>★★</td>
<td>✓</td>
<td>x</td>
<td>Can heat soot deposits directly. Spatial distribution of energy deposition difficult to control / varies dynamically with soot load.</td>
</tr>
</tbody>
</table>
Discussion of candidate electrified DPF technologies and selection

As shown in the preceding discussion, the HCV Project effort has the benefit of a relatively mature state of development of Diesel emissions control technology. In particular, for DPF technologies, there has been more than 20 years of on-going development for (non-hybrid) light duty as well as heavy duty vehicles. Therefore, a suitable DPF system for an HCV powertrain can potentially be chosen out of a wide available array of filtration concepts and regeneration methods (and their combinations).

One very straightforward “adaptation” of the most mainstream of the existing DPF technologies to the hybrid powertrain could be the application of ceramic wall flow substrates, like SiC or cordierite materials, in combination with an upstream electrical resistive heater. Two variants are considered in the tabular comparison in Table 5 above: direct placement of a heater upstream of the entire wall-flow DPF and partitioning of the exhaust flow / DPF and use of multiple heaters and valves to regenerate the DPF one section at a time under low exhaust flow. These substrates’ cost has been dropping steadily in recent years – a significant factor when considering heavy-duty size DPF devices. Such systems could partly separate engine function from DPF management (in line with SP2000 objectives) but will suffer from low energy efficiency and require prohibitively high instantaneous power input in the single heater implementation. This is because for these DPF types the heat is transferred to the soot by heating the exhaust flow to regeneration temperature, and so there is the risk of requiring higher energy than is available from the vehicle power net and certainly beyond the excess from regenerative breaking. Anyway, this would not be the preferred method since there is further efficiency loss in converting chemical (fuel) to mechanical (IC engine) to electrical (e-motor/generator) energy for the DPF. On the other hand, the variant of this concept with a partitioned DPF/heater, incorporating flow restriction valves, presents acceptability issues due to having moving parts in the exhaust line. Therefore, the selection of ceramic wall flow DPF technology seems to be better combined with an off-line (shore power) regeneration concept, where this may be acceptable to the vehicle owners.

Directly heated (conductive) DPF substrates have been shown to require significantly less energy compared to exhaust-gas heating concepts for regeneration, although such systems do need the scheduling of regeneration during low exhaust flow or idling conditions to provide the excellent efficiency. The non-woven Fe-Cr-Al alloy material has been demonstrated as a viable DPF substrate in experimental and retrofit systems. Therefore, modalities for electrically connecting the substrate to a power circuit (and isolation from the DPF canister) are known. These modalities require that the DPF has a modular nature, i.e. to be built up from a number of smaller units incorporating the metallic fiber substrate. This feature is an advantage for integrating an electrically regenerated DPF to the hybrid powertrain since the power requirement can be modulated by employing a larger number of smaller modules if the peak power requirement must be limited for a certain application. Furthermore, the modular nature has been seen to provide additional operational benefits when the regeneration is

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62 Highly Integrated Combustion Electric Propulsion System (Hi-CEPs), European FP6 Programme, Contract: TIP5-CT-2006-031373, Project web site: http://www.hi-ceps.eu/Fe/Site/t02/Home/1#
managed in a sequential manner: only the first module to be regenerated needs to do that at idling conditions – the remaining modules are less sensitive to exhaust flow conditions due to a by-pass effect created by the first cleaned module. Furthermore, in contrast to post-injection regenerated DPFs, the pressure drop reduction is obtained immediately (good for engine efficiency) while subsequent modules require less and less power for their cleaning due to the decreasing amount of exhaust flow that they host as a result of the lower resistance flow paths provided by the previously regenerated modules.

With respect to filtration performance, the mature ceramic wall flow monoliths are the established leaders, with most formulations having initial/clean filtration efficiencies above 70% and acquiring >99% efficiency at relatively low soot loads. The metal filter materials are more challenged in this area, with recent formulations exhibiting initial/clean filtration efficiencies around 40% - 50% and requiring longer loading intervals to attain >99% capture efficiency. However, in the case of the metal fiber materials, prior experience has shown that the direct contact with the soot deposits and the relatively very low thermal mass of the fibrous DPF wall make it possible to obtain pressure drop reduction from short duration electrical power pulses. This permits the consideration of a partial regeneration strategy that will aim to maintain a soot deposit layer on the filter wall at all times, while modulating the pressure drop level to within acceptable values. The pulsed nature of the regeneration process also presents possible synergies with the intermittent / highly transient driving schedule expected for delivery trucks and city buses.

Based on this, and with the motivation to investigate the possibility to leverage all electrical power features of a hybrid platform (high power electrical supply, batteries, regenerative breaking) within the HCV project, it is proposed that the metal fiber DPF concept is the system to be used for the investigation within the WP2400 work package. The goal is to demonstrate that the challenges of the DPF material (lower filtration efficiency than the ceramic monoliths, lower filtration area volume density, manufacturing complexity) will be more than counter-balanced by the synergies with the Diesel hybrid host powertrain, especially for urban driving conditions of a commercial vehicle. Additionally, it is of interest to further drive the adoption of this especially flexible Diesel particulate filter technology for other similar applications.