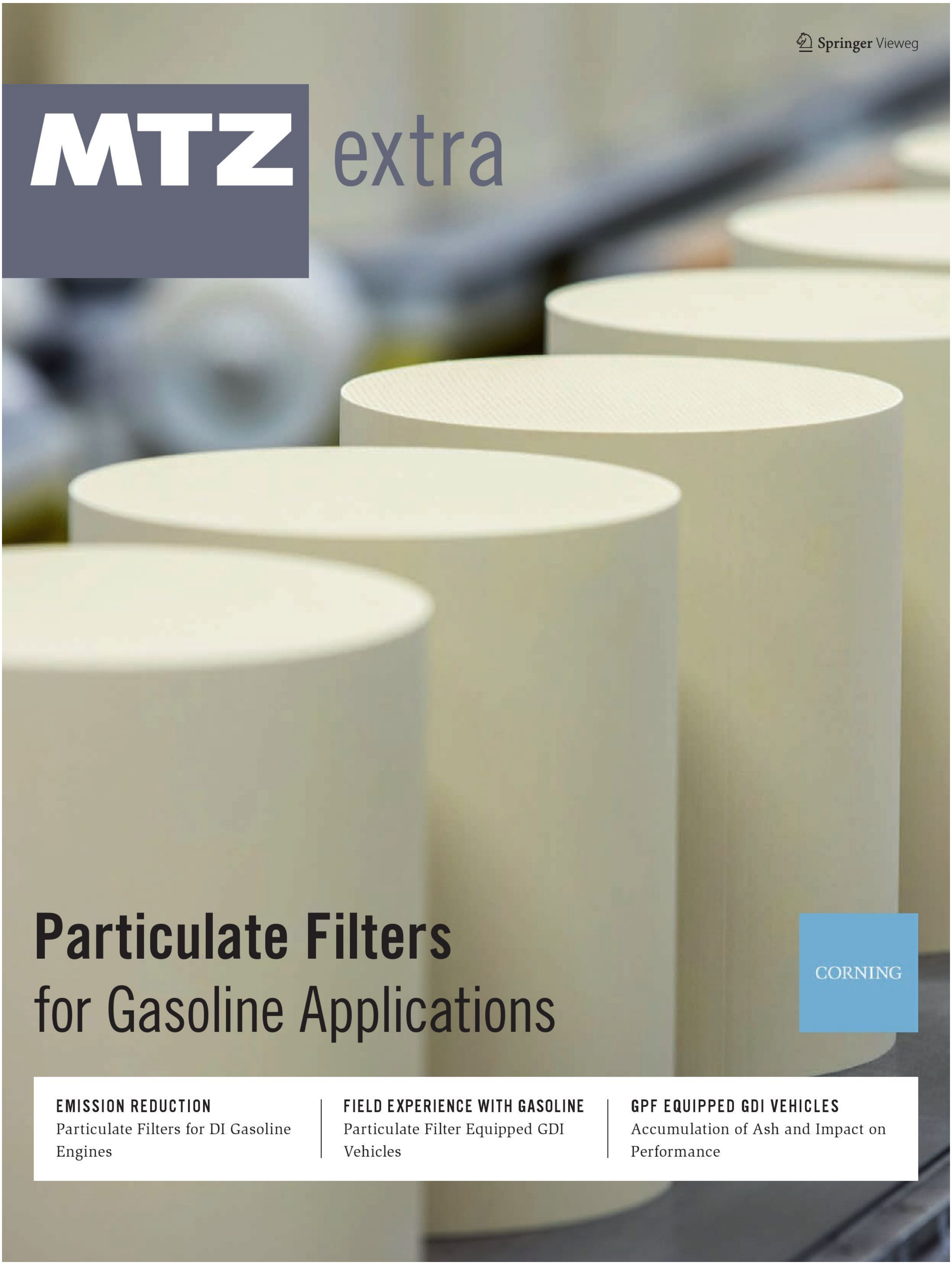

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Particulate Filters
for Gasoline Applications

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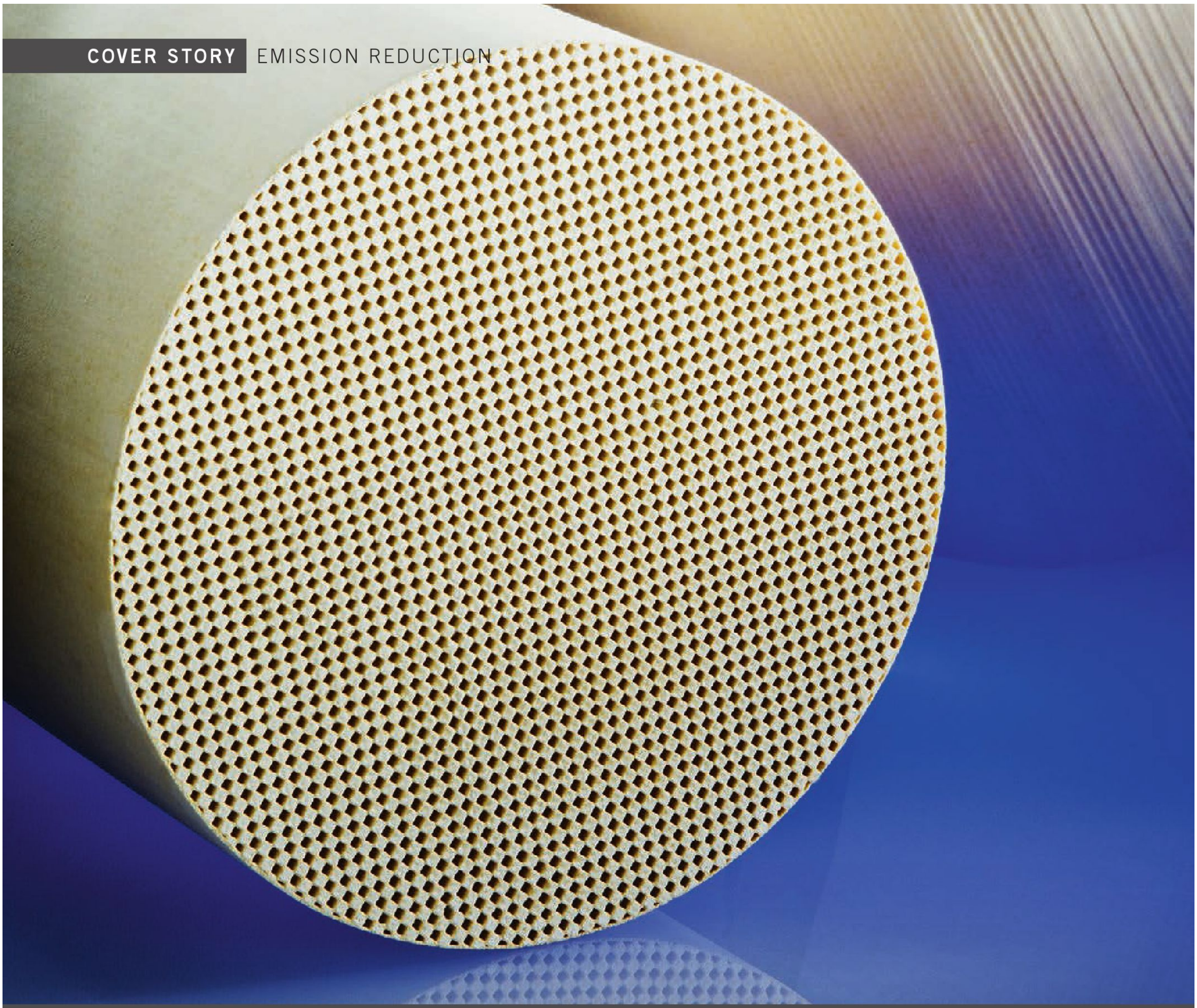
EMISSION REDUCTION
Particulate Filters for DI Gasoline Engines

FIELD EXPERIENCE WITH GASOLINE
Particulate Filter Equipped GDI Vehicles

GPF EQUIPPED GDI VEHICLES
Accumulation of Ash and Impact on Performance



Particulate Filters for DI Gasoline Engines

With the introduction of the upcoming Euro 6b and Euro 6c emissions legislation, gasoline engines will for the first time have to comply with particle number emission limits. Corning presents an overview of the development of particulate filter technologies for application in gasoline engines.

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PARTICULATE EMISSIONS ARE GAINING ATTENTION

Gasoline direct injection (GDI) technology continues to gain share within the segment of vehicles powered by gasoline engines. It is expected that towards the end of this decade the majority of gasoline engines sold in the EU will be based on GDI technology. Studies with current Euro 4 and Euro 5 certified GDI vehicles have shown that these vehicles have particulate emissions which are significantly higher than for gasoline engines based on port fuel injection technologies [1, 2], with particle mass (PM) emissions in the order of 1 to 3 mg/km and particle number (PN) emissions in the order of 10 to 40×10^{11}/km (measured over NEDC). For reference, diesel engine powered vehicles certified to Euro 5 and Euro 6 with DPF have particle number emissions that are below 6×10^{11}/km, the limit defined by these regulations for compression ignition engines.

The interest in low particulate emissions has not changed and is actually gaining attention. Drivers are an increased understanding of the role of carbon black on the global climate [3] and a growing understanding of the relationship between ambient particulate concentrations, especially in urban areas, and its adverse effect on human health [3, 4, 5].

With the introduction of the Euro 6b and Euro 6c regulation [6], particle number limits will be introduced for gasoline engines. The limit is set to 6×10^{12}/km for Euro 6b and with Euro 6c identical to the diesel limit of 6×10^{11}/km. Recognising that the current drive cycle does not capture all operating conditions, work is in progress to define additional test methods to assess vehicles for their real driving emissions (RDE). It will be required to ensure compliance over a wider range of possible operating conditions as well as production dispersion and component drift over time [7, 8].

Particulate filter technologies have been introduced successfully as a robust means to control particulate emissions for diesel powered vehicles. In this article the development and optimisation of advanced filter technologies designed for the requirements of GDI applications will be discussed.

APPLICATION AND SYSTEM CONSIDERATIONS

With respect to the integration of a gasoline particulate filter into the exhaust system, different configurations can be considered. Starting with the reference system with three-way catalyst (TWC), **FIGURE 1** (a), one option is to make no significant modifications to the existing aftertreatment system but add the particulate filter in a downstream position, **FIGURE 1** (b). The functionality of the filter component is limited to reducing particulate emissions. Alternative system layouts are motivated by integrating the filter component into existing packaging space and to use the filter as a substrate for integration of catalytic functionality, **FIGURE 1** (c) and (d). To provide sufficient catalytic conversion the filter has to enable medium to high washcoat loadings.

The engine out particulate emissions of GDI engines are roughly 10 to 30 times lower compared to typical modern light duty diesel engines. This key difference drives many of the performance requirements that lead to different choices for optimal filter technologies compared to DPFs.

With respect to pressure drop, the general desire is to add minimal pressure drop. The filtration needs will depend primarily on the engine out PN emissions. Assuming engine out emissions in the range of 8 to 20×10^{11}/km the filtration efficiency needs to be in the range of 50 to 90 %. Requirements for thermal and thermo-mechanical robustness are assumed to be similar to those experienced by flow through substrates with no extreme heat releases as result of soot oxidation. The differences between add on systems and systems designed for three-way catalyst integration lead to different optimal filter technologies, which will be discussed separately in the subsequent sections.

ADD ON SYSTEMS

A key benefit of an add on system configuration is that no effort has to be made towards the functionality for the gaseous criteria pollutants. Downsides are certainly the additional packaging space required, the addition of a component and the associated pressure drop. Based on the lower engine out soot emissions and the operating conditions in gasoline appli-

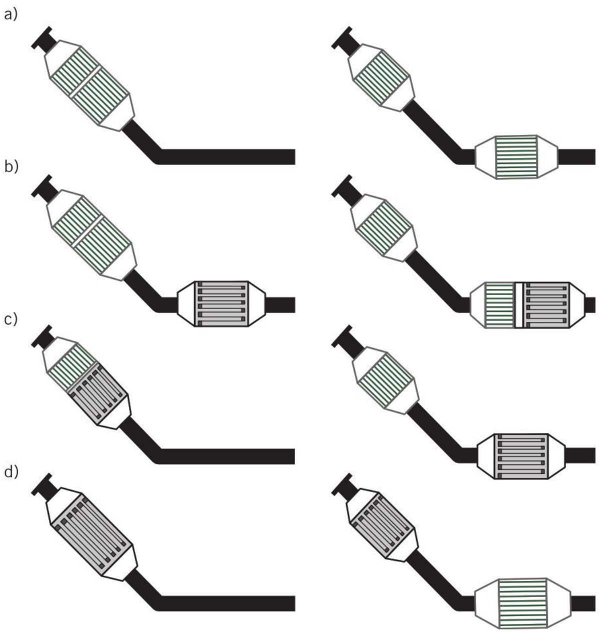

FIGURE 1 System configurations including a particulate filter component (grey): base case (a), add on filter system (b), filter with TWC integration in second or front position (c) and (d), respectively

cations, significantly lower soot loads are expected during operation as compared to diesel applications. Based on test data available are soot loads below 2 to 3 g/l expected. This anticipated low soot load enables the design of filter technologies optimised for lowest pressure drop.

PRESSURE DROP

To derive at an optimised GPF technology for this add on application a wide range of materials, microstructures and filter designs have been screened. Examples of data obtained are shown in **FIGURE 2**. **FIGURE 2** (left) shows the pressure drop response as function of the cell density. All data are shown relative to the 300 cpi and 13 mil (300/13) design of a typical light duty DPF. Experimental data were measured at high flow rate during a power test of the vehicle. In the case of low soot loads, as observed for GPF, the penalty of the frictional losses of high cell density designs dominate over the benefits of a higher surface area. Therefore, lower cell densities such as 200 cpsi are clearly favoured. The effect of the wall thickness is shown in **FIGURE 2** (middle). As expected, a significant reduction in pressure drop is observed as the wall thickness is reduced. Limits are determined primarily by the trade-off with mechanical strength and filtration. Filter designs with 8 mil wall thickness show a good balance with respect to these additional criteria and offer an excellent low pressure drop. Compared to the DPF design with 300/13, a more than 50 % lower pressure drop is expected for a 200/8 GPF design. **FIGURE 2** (right) shows that for advanced particulate filter technologies in uncoated applications the benefit of increasing the porosity is minor, while having the disadvantage of a reduction in mechanical strength. These observations have been considered in the development of the Dev GC technology in 200/8 design.

FILTRATION

Besides the volume of the filter, the key design factors with respect to filtration are the web thickness and the pore size. Porosity and cell density show only a weaker effect on the filtration performance. During the development screening programme, it has been found that the choice of a medium pore size allows for a good balance between the resulting wall permeability and the achievable filtration efficiency. An example of an emission test is shown in **FIGURE 3**. The Dev GC 200/8 filter was installed downstream of the existing TWC component in an underfloor position. The filter had seen very low mileage prior to the emission test (400 km). The data in **FIGURE 3** show that the filtration efficiency is within the targeted range and reduces

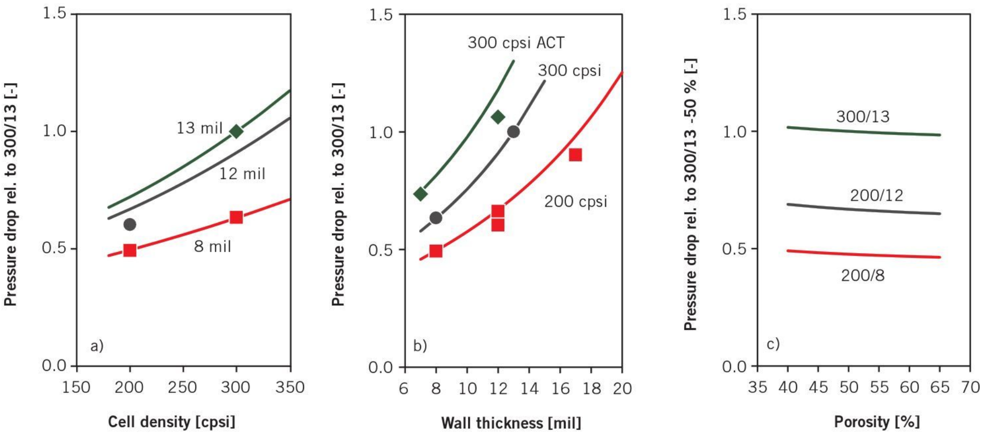

FIGURE 2 Pressure drop for add on GPF concepts (all uncoated, 1.25 l volume, testing on vehicle in underfloor position at rated power, volume flow: 1000 m³/h) (symbols: experiment; lines: modelling results)

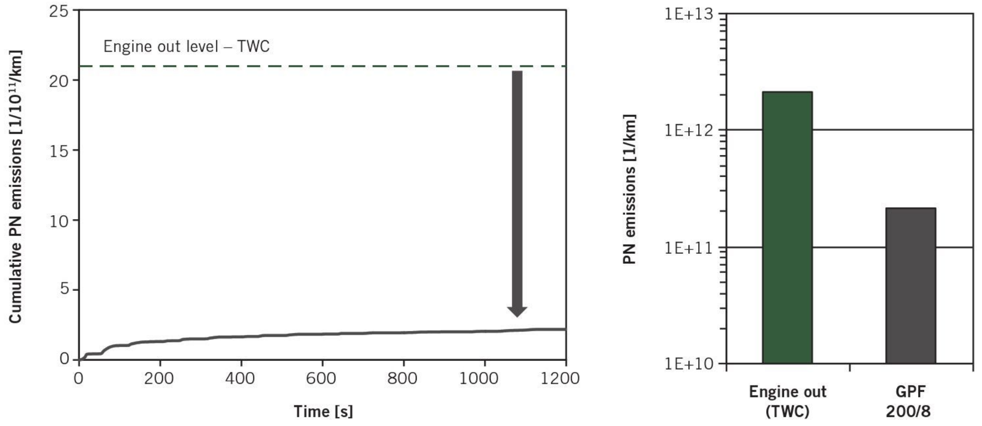

FIGURE 3 PN emissions over NEDC with 1.6-l turbocharged vehicle with an added GPF in underfloor position (GPF: 200/8 design, 1.25 l)

the tailpipe emissions below the required limit.

THERMAL EXPOSURE AND ROBUSTNESS

During normal operation the temperature of the exhaust gas entering the particulate filter does not reach any excessive temperatures. The accumulation and uncontrolled oxidation of soot offers for some potential worst case condition that could lead to higher temperatures and thermal stresses within the filter. The increase in temperature and stress will depend on the quantities of soot accumulated and the conditions of the oxidation. Since the accumulation of soot on the test vehicles has proven to be extremely challenging, with no appreciable soot quantities accumulated even after extended driving, laboratory tests have been developed to assess the conditions that can lead to excessive heat release. For stoichiometric GDI engines the oxygen level in normal operation is typically too low to allow for rapid soot oxidation. In case of fuel cuts, however, the exhaust is rich in oxygen for a short period of time. Key variables that will determine the severity of the heat release during a fuel cut are the amount of soot stored, the temperature, the oxygen concentration and the duration of the fuel cut condition.

These conditions were simulated in laboratory experiments with soot loaded filter samples. The sample was heated in nitrogen (simulating $\lambda=1$) to the target temperature (700 °C) followed by an oxygen pulse (~ 16 % O_2). During the experiment, the temperature within the sample as well as CO and CO_2 concentrations post filter were measured. An example of an experiment is shown in **FIGURE 4**, for which the filter had been loaded to a soot load of 2 g/l, representing a value at the high end of what is expected. In **FIGURE 4** results are shown for the peak temperatures as function of the soot load for three different filter technologies. Also shown as shaded area is the range of soot loads anticipated for typical GPF applications, with values expected to be below 2 to 3 g/l. The results suggest that within this range of soot loads only moderate temperature peaks are expected for the pressure drop optimised Dev GC technology in 200/8 geometry. If significantly higher soot loads would be expected, technology options exist that provide for a higher volumetric heat capacity. Two examples of such technologies are shown

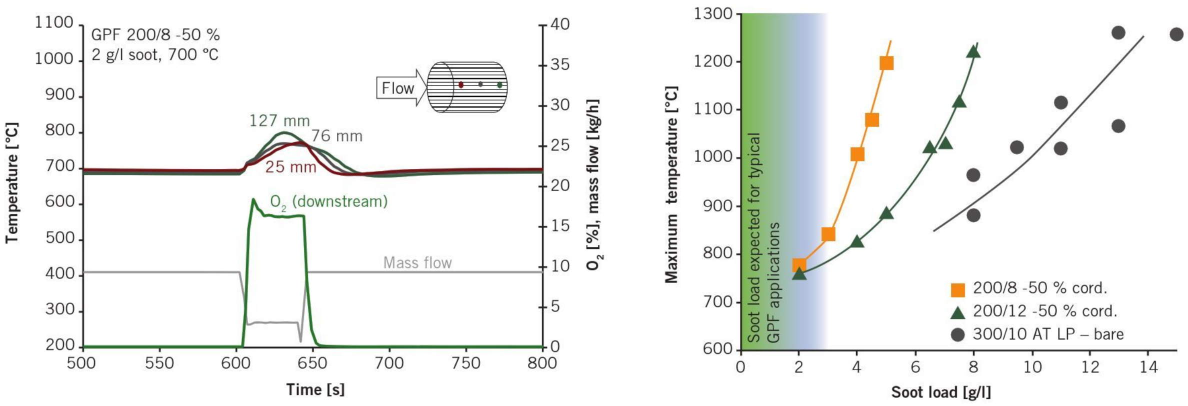

FIGURE 4 Lab scale experiments simulating fuel cuts with a hot, soot loaded GPF: example of the experimental procedure (left), maximum temperatures observed in the filter as function of the soot load (right)

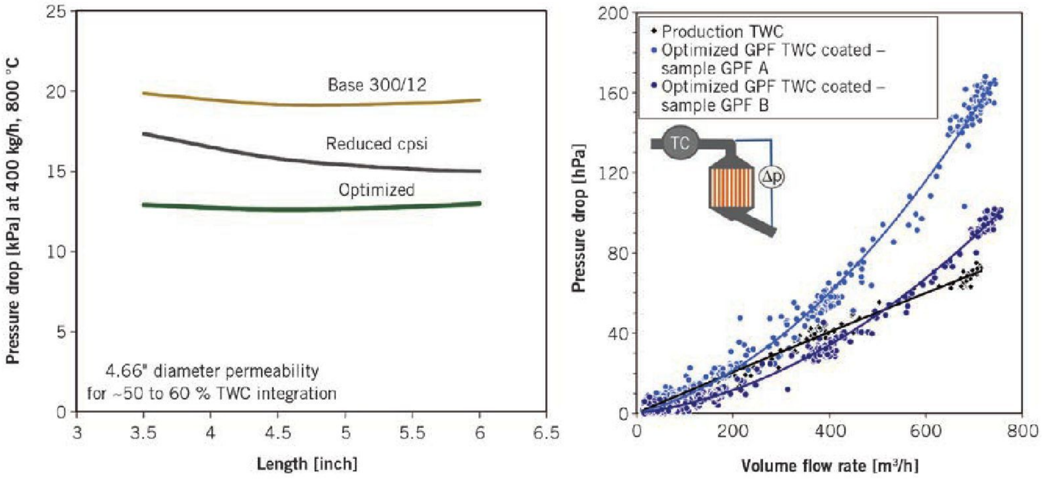

FIGURE 5 Pressure drop of different GPF technologies with TWC integration: simulated pressure drop as function of filter length (left), experimental pressure drop data measured during power test (right) (sample GPF A has same diameter as production TWC, sample GPF B has 20 % larger diameter)

in **FIGURE 4**, one based on cordierite the other on DuraTrap AT LP 300/10 [9]. It has to be mentioned that both technology options shown for cases with very high soot load requirements come with a penalty in clean pressure drop compared to the 200/8 technology. They are, however, still significantly lower when compared to the base case DPF technologies in 300/13 cell geometry.

SYSTEMS WITH THREE-WAY CATALYST INTEGRATION

The integration of three-way catalyst functionality into the filter substrate is an attractive option. Their general feasibility from a catalytic performance perspective was demonstrated in recent publications [10, 11]. In addition to the characteristics discussed above the filter component for three-way integration has to meet additional requirements to enable an efficient catalyst performance.

PRESSURE DROP

The amount of catalyst that needs to be integrated into a GPF is appreciably higher compared to typical diesel applications. This difference in coating levels has significant impact on the design and selection of an optimised filter technology for minimal pressure drop. For high washcoat loads higher porosity levels are beneficial. In **FIGURE 5** pressure drop data are shown for filters with high porosity in the range of 60 to 65 % and high washcoat loadings. Data for a 300/12 design, common in DPF's, are provided as reference. The optimisation of the cell design for this three-way catalyst integrated GPF application was motivated by the fact that the pressure drop results obtained initially with this DPF configuration did not meet the requirements. The additional examples shown in **FIGURE 5** represent cases with reduced cell density and an optimisation of the web thickness. Both advanced designs with the Dev GC HP technology enable a significant decrease in pressure drop.

Shown also in **FIGURE 5** are pressure drop data measured on a vehicle. Data are provided for the series production three-way catalyst as well as two three-way catalysts coated Dev GC HP filter in the optimised cell design. The two GPF samples had 33 to 48 % larger volume, respectively, with the first sample GPF A having the same diameter as the three-way catalyst but a longer length and the second, GPF B, having a ~ 20 % larger diameter but same length as the series production three-way catalyst. From the data it can be seen that at low to medium flow rates the two GPF components have a pressure drop comparable to the flow through three-way catalysts. At higher flow rates the GPF A component with the diameter equal to the production three-way catalyst has a higher pressure drop, as expected. The data for the component with larger diameter, GPF B, show a pressure drop comparable to the flow through three-way catalysts.

FILTRATION AND EMISSIONS

The filtration performance of the above discussed three-way catalyst coated Dev GC HP technologies has been found to meet the targeted efficiencies. Even for small filters of 1.25 l volume and the resulting high space velocities, efficiencies in the order of 70 to 80 % have been

	REFERENCE SUBSTRATE	HIGH POROSITY CORDIERITE GPF TECHNOLOGIES			HIGH POROSITY SIC
Cell geometry	600/3	Base design 300/12	Reduced cell density	Optimised design	300/12
Matrix density	100 %	127 %	105 %	91 %	183 %

FIGURE 6 Comparison of thermal mass (density) of different high porosity GPF designs and a thinwall flow through substrate

	ADD ON GPF	TWC INTEGRATED GPF
Technology	Dev GC	Dev GC HP
Cell density	200 cpsi	200 cpsi 300 cpsi
Web thickness	8 mil	Optimised
Material	Cordierite	Cordierite
Porosity	Medium	High

FIGURE 7 Summary of optimised filter technologies for gasoline applications

observed over cold start NEDC in the fresh and clean state. Measurements performed in limited durability experiments have shown improvements in filtration efficiency as mileage is accumulated.

With respect to the catalytic performance, one important filter and substrate parameter to consider is the heat up behaviour during cold start. A key parameter determining the heat up behaviour is the thermal inertia, represented by the product of heat capacity and bulk density. The low intrinsic material density of the cordierite ceramic combined with the low thermal conductivity enable fast light off designs, presenting a key differential advantage versus alternative material options. In **FIGURE 6** the thermal inertia of different filter designs is compared, all with a high porosity > 60 %. The values are provided relative to the thermal mass of a thinwall 600/3 flow through substrate, which is used as reference. The cordierite based design with 300/12 used early in the development programme shows a clear disadvantage, having about 27 % more thermal inertia. The high porosity SiC option shown is even worse. This high thermal mass was found to be detrimental to the light off performance of a close-coupled, TWC coated GPF. The advanced Dev GC HP designs, on the other hand, show comparable (105 %) or even favourable (91 %) thermal inertia compared to the 600/3 reference substrate technology.

THERMAL EXPOSURE AND ROBUSTNESS

Similar laboratory experiments simulating fuel cut conditions with the soot loaded filter preheated to 700 °C in nitrogen, as described above for uncoated filters, have been performed with TWC coated GPF technologies. The lab tests showed for the expected maximum soot loads of 2 to 3 g/l of soot, temperatures in the range of 1000 to 1050 °C, comparable to the range of temperatures commonly used for catalyst ageing. The lab tests were confirmed in vehicle tests in which filters were loaded externally with soot prior to installation in close-coupled position and then tested under realistic fuel cut conditions. The fuel cut was initiated after a hard acceleration with high exhaust and filter temperatures in the range of 680 to 750 °C. For initial soot loads of ∼ 3 g/l the maximum temperatures observed within the filter were 1000 to 1040 °C, in agreement with the lab data. It should be mentioned that these temperatures last only for a few seconds versus several hours used in oven ageing experiments and the impact on catalyst ageing is expected to be moderate. An interesting observation made was that no further exotherm release was observed during any subsequent fuel cut, suggesting that all the soot was oxidised during one event.

SUMMARY

As discussed in the previous sections are the requirements for particulate filters for gasoline applications significantly different from those in diesel applications. Soot mass limit and filtration requirements are somewhat relaxed while at the same time, it is crucial to enable lowest pressure drop. Based on current understanding, are two different system configurations anticipated for gasoline particulate filter applications. The requirements of both system architectures lead to different technologies as optimised solution, which are summarised in **FIGURE 7**. The advanced filter technologies described and discussed address one of the main technical challenges of GPF's, the pressure drop added to the exhaust system, and minimise the accompanied penalty.

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Field Experience with Gasoline Particulate Filter Equipped GDI Vehicles

Particulate filters for gasoline applications will in the future become a valued contributor towards a sustainable, future mobility. Corning introduces particulate filter technologies available today and provides a broad overview of practical experience gained with these new gasoline particulate filter technologies on vehicles and engine bench. Own fleet tests show a significant reduction of particulate emissions.

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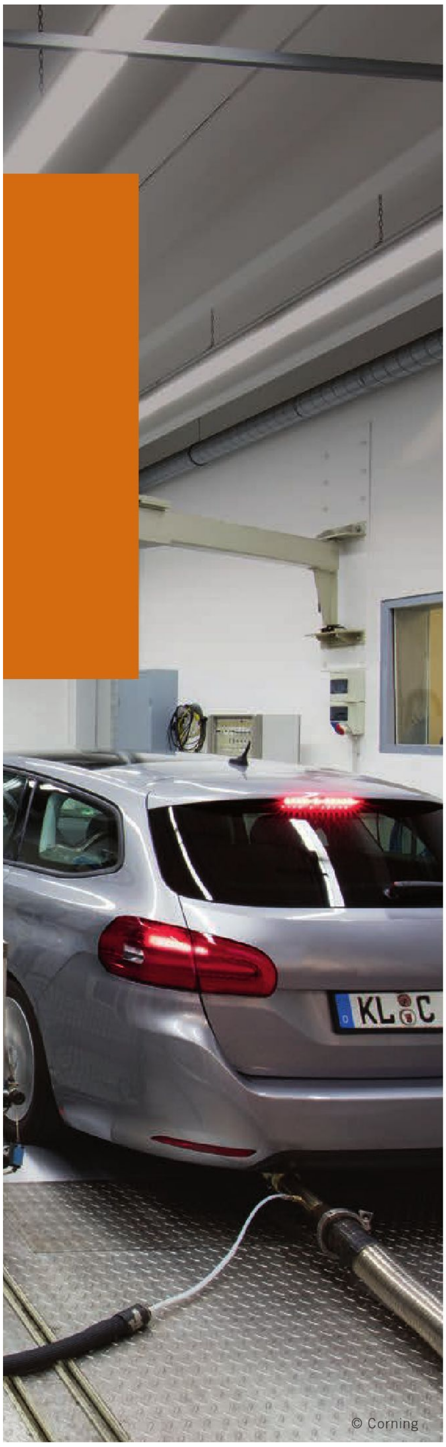
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NEW EMISSION GOALS

Particulate filters for gasoline applications (GPF), also referenced as Otto Particulate Filter (OPF), are one of the new technologies selected to address the upcoming Euro 6d regulations starting in 2017. The implementation of GPF for major platforms has been announced recently [1], [2]. In general, OEMs are in a position where they have to decide whether they rely on improvements of the internal combustion engine to reduce particle formation or if they introduce new aftertreatment technologies to address particulate emissions [3] or combinations of both. Based on the recent public announcements one could conclude that aftertreatment is no longer seen as the unloved necessity, but became a valued contributor towards sustainable future mobility. These changes in mind-set drive the introduction of GPF not only for "high emitting" engines, but GPFs will be also used on the most advanced "clean" engines. For these engines the GPF will enable Real Driving Emissions (RDE) standards [4] with low conformity factors that will be applied to emissions measured during on-road testing. The second important advantage of GPFs will be that they have the potential to compensate for all kind of drift-effects that could lead under certain conditions to a change in raw emissions.

Since the start of the development of particulate filters for gasoline applications several years ago, significant progress has been made with respect to the filter technologies available today and the understanding of the application requirements on customer vehicles. First field experience has been gained with filters tested over extended mileage on vehicles in a large number of programs.

GASOLINE PARTICULATE FILTER TECHNOLOGIES

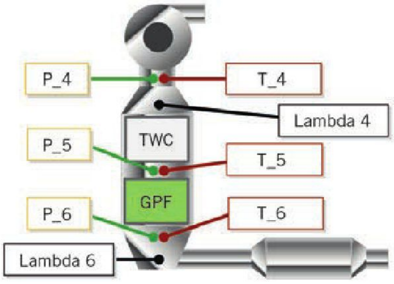
To enable the various applications two families of GPF technologies have been developed [5], summarised in **TABLE 1**. For applications in which the filter is added without or only with a low level of additional catalyst the DuraTrap GC filter technology has proven to provide lowest pressure drop at very high filtration efficiency. This filter technology has a porosity of approximately 55 % and the common design used is based on a cell density of 200 cells per inch (cpsi) and a nominal web thickness of 8 mil (1 mil = 25.4 µm). For applications in which a significant amount of three-way catalyst (TWC) is integrated into the filter, the family of DuraTrap GC HP filter technologies has been developed. They all have very high porosity of approximately 65 % to enable high catalyst loadings. They differ in their median pore size, facilitating a selection that allows to trade-off the needs for filtration versus the penalty in pressure drop. The most common cell design is a 300 cpsi honeycomb with thin webs of 8 mil, representing the result of extensive optimisation for lowest coated pressure drop and catalyst efficiency. In some applications products with somewhat thicker webs of 12 mil are used. Both technologies have been scaled to production and are produced in a wide range of contours and sizes.

EXPERIENCE FROM VEHICLE DURABILITY PROGRAMS

With gasoline particulate filters being a new technology and application a large number of on-road vehicle test programs were performed as part of the product development and validation. In these programs the GPF technologies have been tested on more than 25 vehicles,

Filter technology	DuraTrap GC	DuraTrap GC HP
Material	Cordierite	Cordierite
Cell density	200 cpsi	300 cpsi
Web thickness	8 mil	8 mil, 12 mil
Porosity	~55 %	~65 %
Application	Uncoated to low catalyst loading	Low to high catalyst loading

TABLE 1 Gasoline particulate filter technologies (© Corning)



Vehicle data	Exhaust system data
From OBD: speed, RPM, engine-load, coolant temp., add. exhaust-mass flow sensor	T and P pre TWC T and P pre GPF T and P post GPF λ / O_2 pre and post GPF

FIGURE 1 Example of schematic instrumentation of test vehicles equipped with GPF (© Corning)

covering all vehicle segments and engine displacements from 1 to 3 l, including dedicated test vehicles as well as 12 company cars operated under normal customer profiles. By end of 2016 a cumulative mileage of roughly 1.7 million km has been collected on Corning operated vehicles. In the following sections results from some selected programs will be discussed.

ON-ROAD DURABILITY USING DIFFERENT ENGINE OIL FORMULATIONS

During use particulate filters collect not only soot particles emitted by the engine but also any inorganic particles that find their way to the filter. Challenge with these inorganic particles, usually referenced as ash, is that, in difference to the soot trapped, they cannot be oxidised and removed during operation. As a result they accumulate over mileage and can lead to an increase in the filter pressure drop. Today, very limited experience exists with respect to ash accumulation for conventional gasoline aftertreatment systems. The inorganic components present in engine oil formulations are known to be a major source for ash collected in particulate filters. One of the test programs was designed to explore the impact of the sulfated ash content of the engine oil. Two identical C-segment vehicles with 1.2-l T GDI engine were used for the program. Both had been retrofitted with a GPF in close-coupled position directly behind the TWC, with no changes to the engine management. The filter volume was comparable to the engine displacement. Both vehicles had been instrumented with a data acquisition system and number of additional temperature, pressure, mass flow and lambda sensors and were operated with additional sand filled dummies to increase the vehicle load. A schematic of a typical vehicle instrumentation used in the GPF programs together with some generic information on the conditions during this specific program is provided in **FIGURE 1** and **FIGURE 2**. The two vehicles were operated under statistically identical conditions on real roads, but with different oil formula-

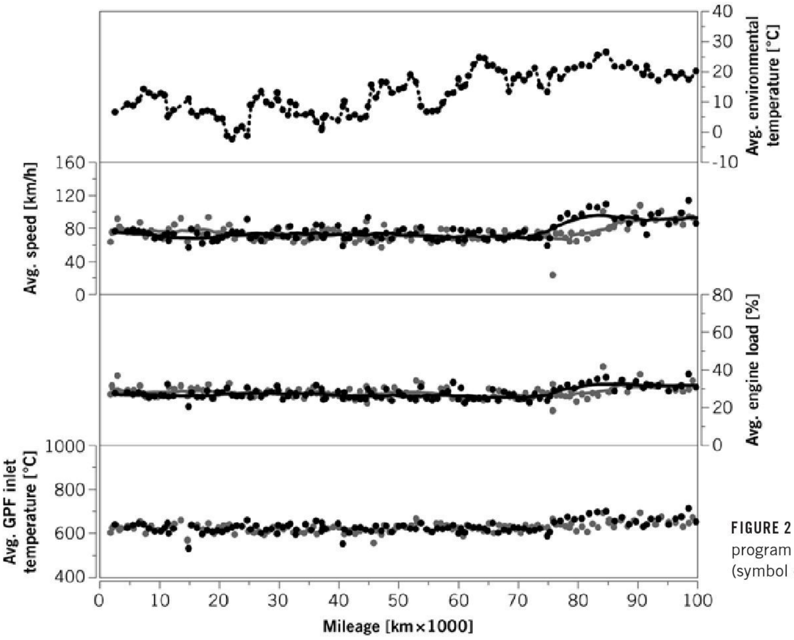


FIGURE 2 Operating conditions for GPF durability program with two vehicles with two types of oil (symbol color indicates vehicle A and B) (© Corning)

tions having a sulfated ash content 0.56 and 1.25 %, respectively. Both oils were provided by Lubrizol, a specialist for engine oil additives. The higher ash oil is also viewed as a representative for oil formulations which might be used in China, where GPFs are expected to be broadly deployed as well for the upcoming China 6 regulation. Results from this durability trial are provided in **FIGURE 3**. Shown are the particulate number (PN) emissions over three test cycles (NEDC, WLTC and RTS-95, the latter as surrogate for RDE), the mass of ash found in the GPFs and the pressure drop measured for the two filters from both vehicles. The pressure drop was measured on a cold flow laboratory bench to allow for better accuracy. From the emission data one can see that the GPFs enabled low particulate emissions over all cycles evaluated

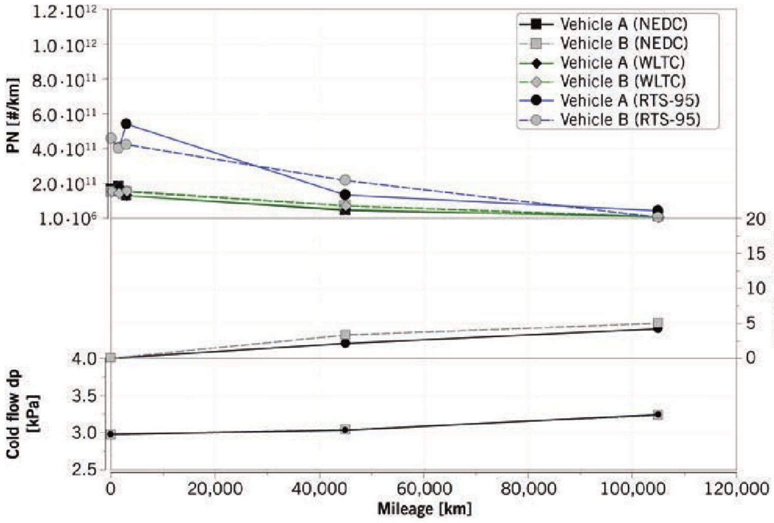


FIGURE 3 Emission results (top), ash mass (middle) and pressure drop (bottom) observed for the GPF durability program with two vehicles with two types of oil; black symbols = vehicle A with 0.56 % SAPS oil, grey symbols = vehicle B with 1.25 % SAPS oil (© Corning)

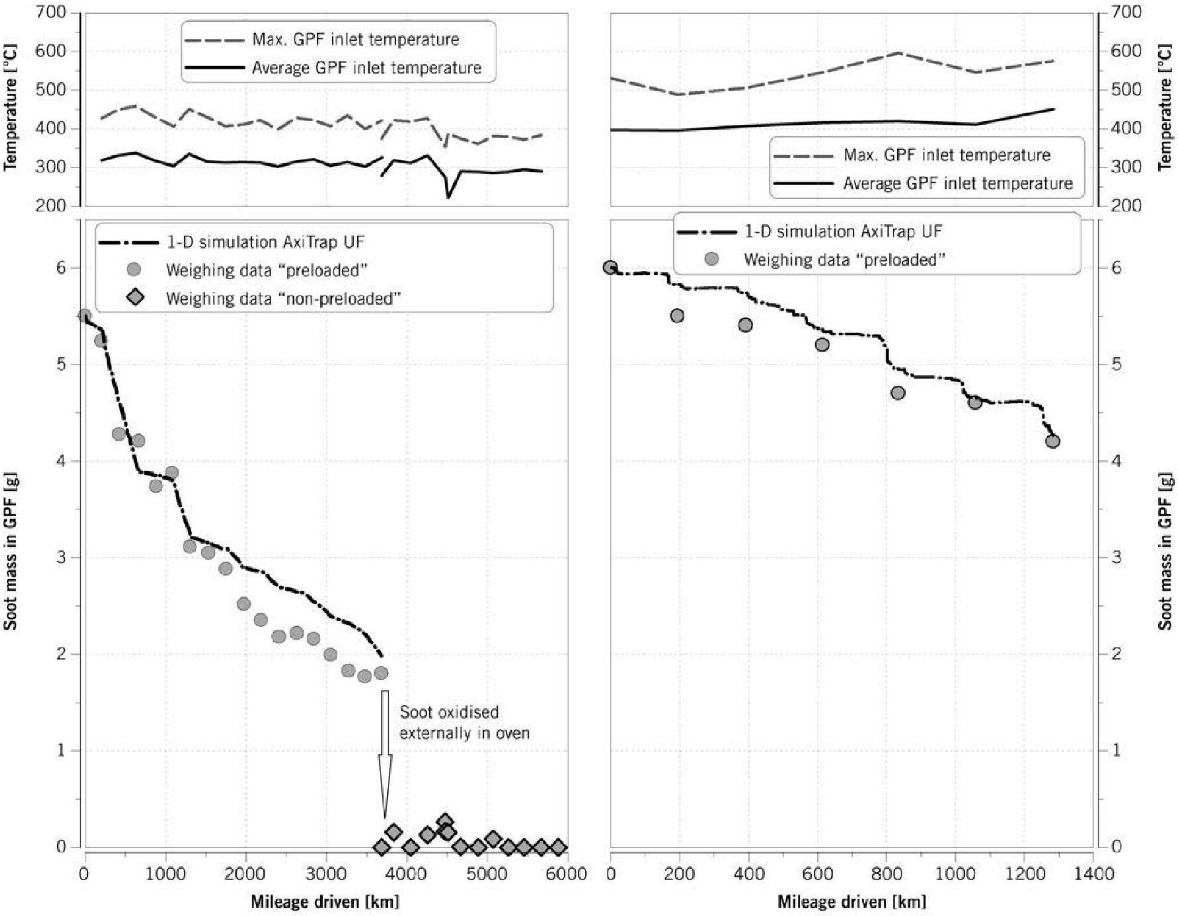


FIGURE 4 Evolution of soot load and related inlet temperature for GPF's located in underfloor; results are obtained on two different vehicles, both operated in city driving with maximum 50 km/h (© Corning)

from the start of the test. One can also see that the emissions steadily decrease over mileage, which is explained by the built up of an ash membrane which further enhances the filtration. The negative effect of the ash can be seen from the pressure drop data. In both cases an identical evolution was found, yielding an increase by roughly 10 % over 100,000 km. From the ash mass data the difference in oil formulations can be seen with somewhat higher values for the higher ash oil. It should be noted, however, that both vehicles had very low oil consumption which could explain the low quantities of ash found in both filters at least to some extent. In other programs larger quantities of ash per kilometer had been observed. Overall, no problems were observed with the two vehicles retrofitted with GPF throughout the entire program.

SOOT MANAGEMENT

While the examples discussed in the previous section used a GPF in close-coupled location, where temperatures are expected to be sufficiently high to enable passive regeneration of soot during fuel cuts with oxygen reaching the exhaust [6], the situation is less clear for applications in which the GPF is located in a colder underfloor position. While in the majority of the vehicle experiments it was not possible to accumulate significant quantities of soot, applications exist in which the rate of soot emitted exceeds the amount of soot that can be oxidised passively. To explore this further a number of experiments with different vehicles and filter installations have been performed. Because of the inability to accumulate soot on the vehicle, the GPFs in these experiments have been loaded with soot ex-situ, prior to the experiment to represent an extreme case of a filter that was operated in a way that would result in the accumulation of soot. The soot loaded filters were then installed onto the vehicle. The vehicles were operated on public roads under different low load conditions, resulting in relatively low exhaust temperatures. During the experiments the soot mass in the filter was monitored daily by weighing of the filter. Examples of such experiments are shown in **FIGURE 4** for filters installed on two different vehicles which had been operated in city driving with a maximum velocity of 50 km/h. The average and maximum temperature at the filter determined over the cycles is also shown. Both vehicles had relatively low engine out particulate emissions. In addition to the experimental soot mass are data shown as obtained in detailed numerical simulations using the measured operating conditions (flow, temperature, oxygen) as boundary conditions. In these examples a passive regeneration of the filter is possible. The mass of soot is successively reduced during short fuel cut events, even at relatively low exhaust temperatures. The latter can be seen from the simulation data in which the small “steps” in soot load are usually linked to short fuel cuts with oxygen in the exhaust.

While the fuel cuts during which the oxygen level in the exhaust approaches ambient levels are desired for the passive regeneration of accumulated soot, they also represent a potential worst case if significant quantities of soot have been accumulated and the fuel cut occurs at a high temperature. In this case the rate of soot oxidation is high and the resulting heat release can lead to an increase in filter temperature and significant thermal stress. While this situation can in general be evaluated on vehicle it is more efficiently done on engine bench, where high soot loading and the conditions can be well defined. An example of such an experiment is revealed in **FIGURE 5**. Shown is the exhaust temperature upstream of TWC (T4) and GPF (T5) as well as the maximum temperature inside the GPF. Once the exhaust temperature has been increased to the target value, in

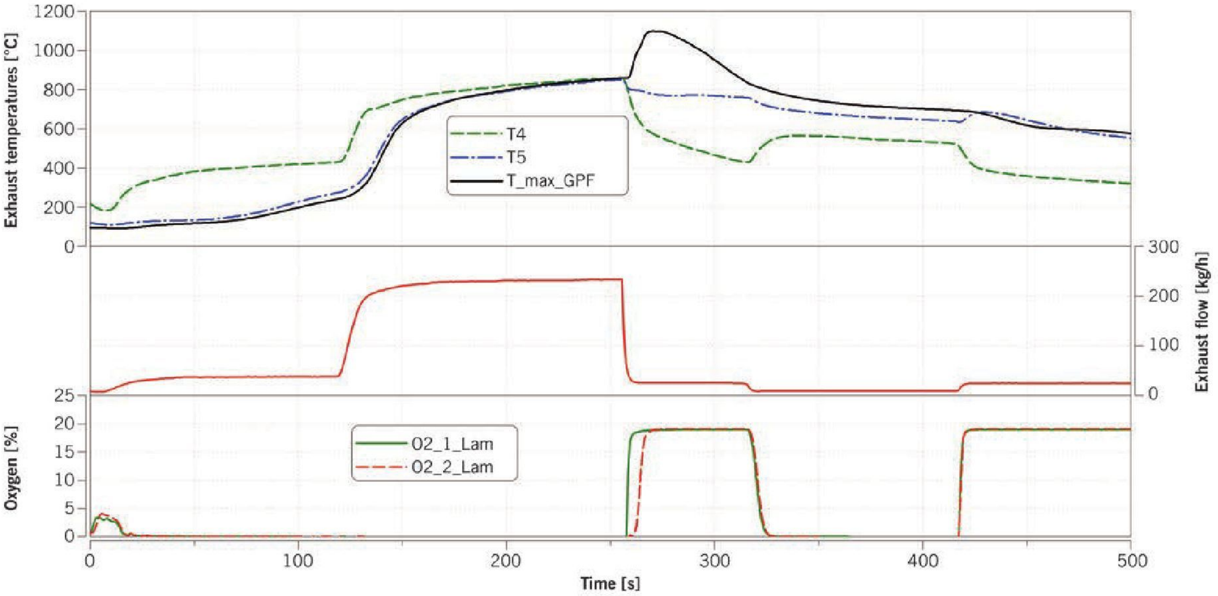


FIGURE 5 Engine bench fuel cut procedure to test for severe soot oxidation in GPFs (© Corning)

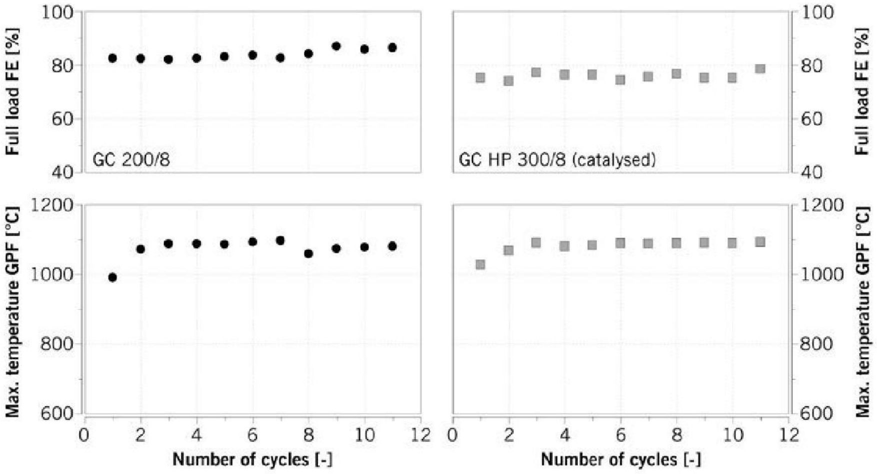


FIGURE 6 Repeated survivability testing one engine bench with soot loaded GPFs; shown is the maximum filter temperature recorded during the fuel cut (lower row) and the filtration efficiency measured after the exposure (upper row) (© Corning)

this case approximately 870 °C, the fuel cut is initiated. This can be seen from the oxygen traces measured up and downstream of the GPF. The filter had been loaded with soot prior to the experiment, with the soot mass applied significantly exceeding the value we had observed in our vehicles. As this represents a potential worst case, a large number of filters from both technologies have been tested for their thermo-mechanical robustness under such severe conditions. Examples for engine bench experiments in which a filter has been exposed to more than 10 of such events, with a maximum temperature between 1050 and 1100 °C, are revealed in **FIGURE 6**. The left diagram shows the results for GC 200/8 and the right those for coated GC HP 300/8. Documented are the maximum temperatures observed and the related filtration efficiency measured after the soot burning event. As can be seen the filtration did not change in these tests, demonstrating the robustness of the filters.

FIELD TRIAL USING A FLEET OF COMPANY CARS

As the experience with a significant number of dedicated test vehicles had not shown any issues with respect to soot accumulation or other operational problems, a large fleet experiment had been initiated in which 12 GDI vehicles of the normal company car fleet had been retrofitted with GPFs. All cars were Euro 5 or Euro 6b certified and had their first registration in 2014 or 2015. No changes were made to the engine management. The vehicles from different brands and makes in this fleet trial cover a wide range of vehicle segments (C-, D-, E-segment and SUV) and engines with displacements between 1.4 and 3.0 l. The retrofitted filters were in most cases uncoated and installed in the underfloor position. However, two vehicles were equipped with coated GPFs in close-coupled location. No instrumentation or data acquisition was applied. Objectives of this trial were to collect broad field experience with the filter technologies under normal customer profiles and also to collect more information about the accumulation of ash on a large number of filters. To monitor the filter performance the emissions of all vehicles were measured prior to the retrofit and after the retrofit with the GPF. Results from these PN measurements are shown in **FIGURE 7**. The reduction in PN emissions after the retrofit with the GPF is evident. Additional emission measurements have been performed on each vehicle after 3000 km and after 6000 to 10,000 km to

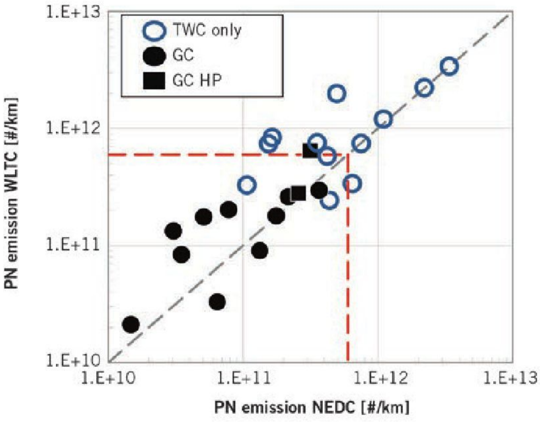


FIGURE 7 Original particulate number emissions from company car fleet without GPF and directly after the retrofit (© Corning)

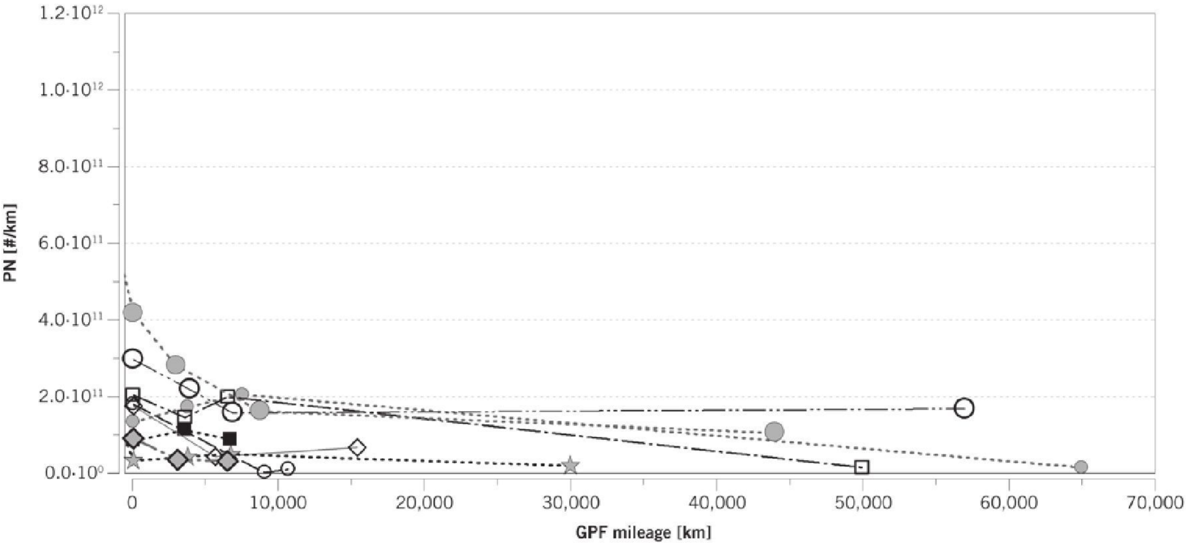


FIGURE 8 Evolution of the WLTC particulate number emissions from company car fleet; different symbols represent the different vehicles (© Corning)

obtain information on the initial evolution of the filtration performance. The trial is still in progress but intermediate emission results are already available with several vehicles having reached already between 40,000 and 70,000 km. The results are shown in **FIGURE 8**. As it was already observed in the example discussed above the PN, emissions for all vehicles are decreasing with mileage. Besides the excellent emission performance no issues have been reported so far by the drivers of the cars.

SUMMARY

First experience with gasoline particulate filters operated on a broad range of standard Euro 5 and Euro 6b vehicles on public roads has been collected over extended mileage during the past few years. In the test activities different application aspects have been explored, ranging from general durability and emission performance to the effect of ash, the management of soot and the robustness to some severe conditions. The operation was done in dedicated test campaigns and high mileage durability vehicles as well as with a fleet of normal customer vehicles. Examples of these experimental studies and experiences made have been summarised in this paper. Up to now the experience made with GPFs in the vehicle tests has been positive.

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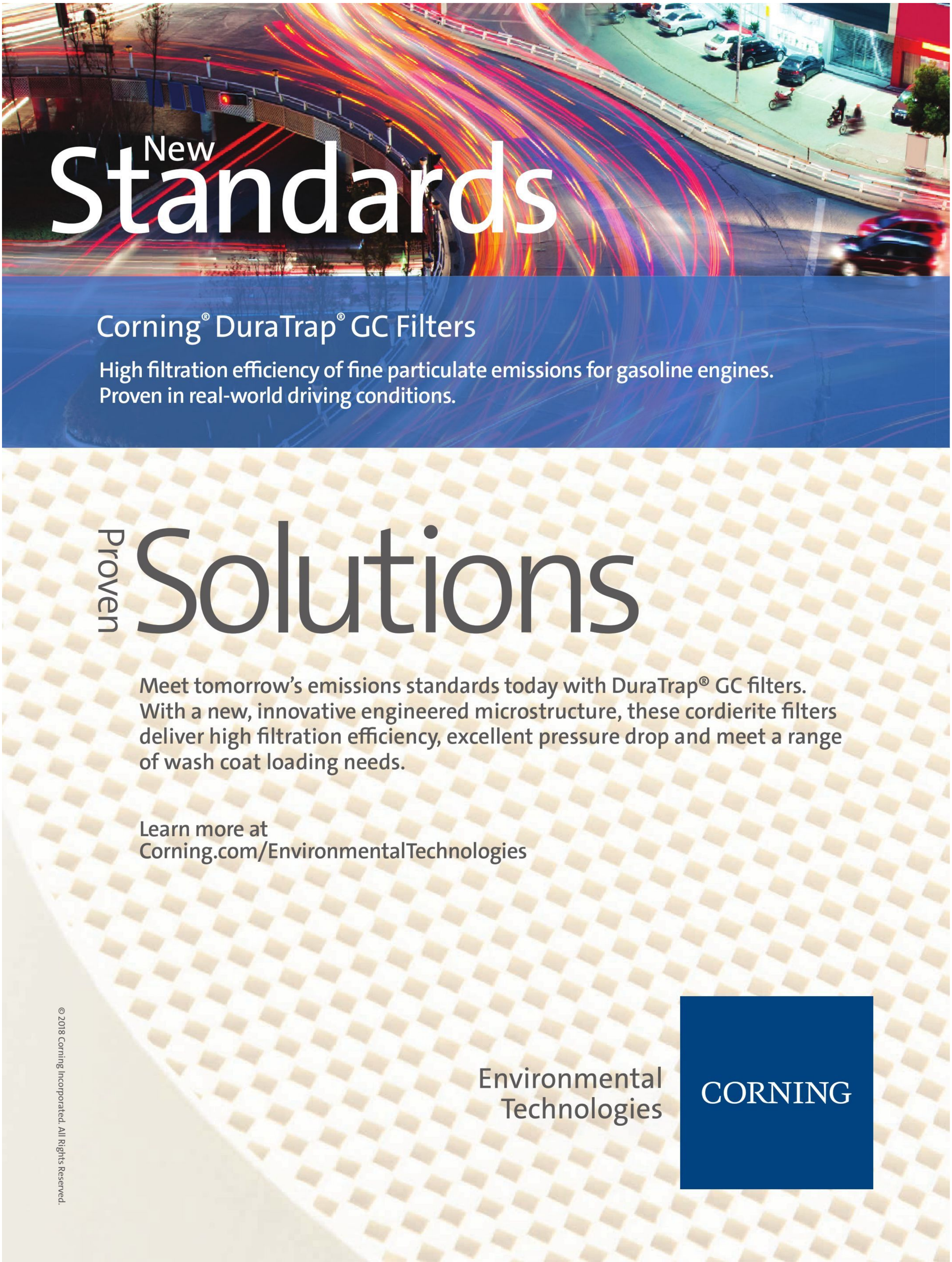

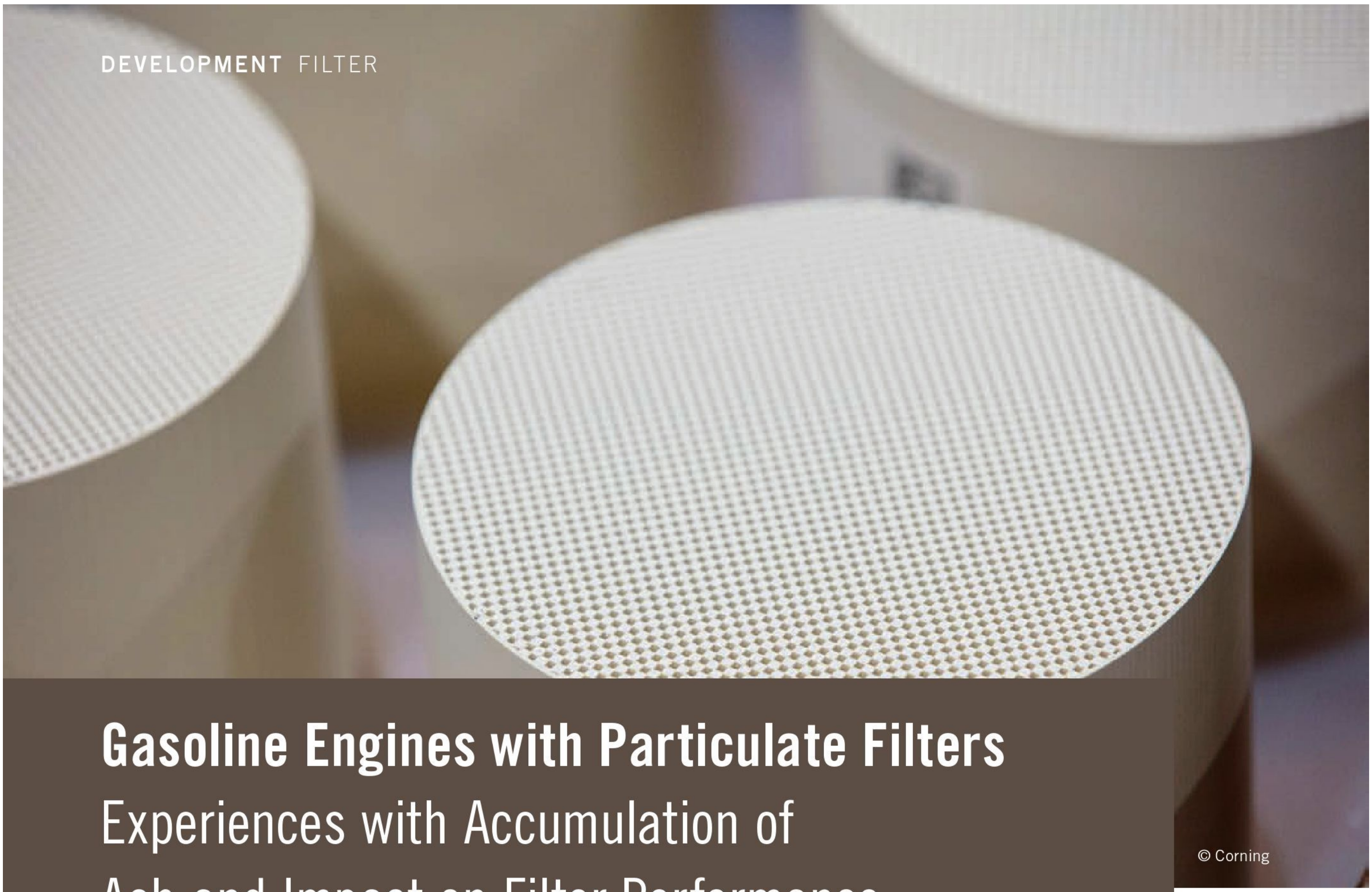

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Gasoline Engines with Particulate Filters

Experiences with Accumulation of Ash and Impact on Filter Performance

In the future, gasoline particulate filters will be part of a sustainable, environmentally friendly and future-proof mobility in exhaust aftertreatment. Corning reports on experiences from endurance tests with gasoline particulate filters and how their operating behavior develops over the service life. In particular, the topic of stored ash and its effects will be examined in detail.

INTRODUCTION

The development of Gasoline Particulate Filters (GPF) started about one decade ago. For a long time it was uncertain if this new aftertreatment technology would become a standard element in modern gasoline powertrains or if it would remain limited to niche applications. Today, with the new Euro 6d regulations in effect and the upcoming China 6 regulations this question has been answered. Both contain strict requirements for particulate emissions under laboratory as well as real world driving conditions. Nearly all modern direct injection gasoline vehicles in China and Europe will be equipped with a gasoline particulate filter, as well as a large number of vehicles with port fuel injection in China. The gasoline particulate filters installed help to significantly reduce the number and mass of particulates emitted, addressing regulations as well as public health concerns. With gasoline particulate filters still being a “young” technology, a wide spectrum of aftertreatment architectures are deployed, requiring different filter technologies. One differentiating factor is the location of the GPF in the exhaust line. While some systems utilize filters installed in an underfloor location, downstream of the flex-pipe, others utilize GPFs located close-coupled to the engine, often in tandem with a Three-way Catalyst (TWC) or even replacing the close coupled TWC [1-3]. A main differentiation with respect to the selected filter technology is whether the filter is bare (filtration function only) or is coated with some catalyst to provide TWC functionality and filtration efficiency. Filter technologies used for coated applications usually have a higher porosity and cell density compared to filters in uncoated applications, both optimized for their pressure drop to filtration trade-off as

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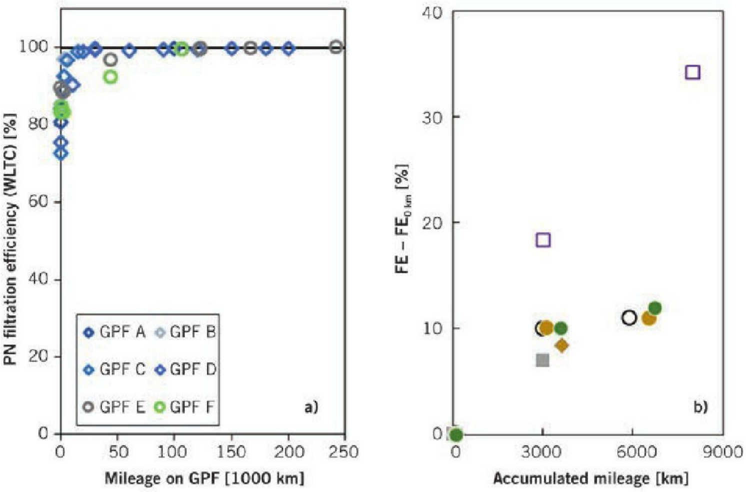

FIGURE 1 Evolution of filtration efficiency with mileage (data measured on different test vehicles and filters over WLTC; different symbols represent different filters) (© Corning)

well as their effectiveness as catalyst support, where applicable. Two examples are Corning DuraTrap GC HP 300/8 and GC 200/8 filter technologies [4].

While the first systems with GPF have been developed and are on the market today, there still exists a need to further enhance the application understanding, especially with respect to durability information and the evolution of the filter performance over its useful life. In a previous contribution [4] results on tests with a larger number of vehicles that had been retrofitted with a GPF and operated on public roads over an extended mileage were reported. Focus was the reduction in Particle Number (PN) emissions as well as the management of the accumulated soot. Objective of this new contribution will be to build on this previous work and expand towards a deeper understanding of the influence the accumulated ash has on the filter performance.

PERFORMANCE IMPACT OF ASH

Gasoline particulate filters collect not only the carbon-based soot particles emitted by the engine but also inorganic particles in the exhaust gas. These inorganic particles are typically referenced as ash. In difference to the carbon-based particles, these inorganic particles cannot be regenerated by oxidation and they accumulate over the life of the filter. This accumulation of ash results in an improvement in filtration efficiency. This is illustrated in **FIGURE 1** (a) for some durability vehicles with coated and uncoated DuraTrap GC HP and GC filters with mileages up to 240,000 km. As shown, the filtration efficiency increases fairly rapidly for all filters, reaching high levels for the majority of the mileage. A closer look at the change in filtration efficiency over the initial mileage of less than 10,000 km is shown in **FIGURE 1** (b). To better illustrate the effect, the incremental increase in filtration efficiency is plotted in this case. The data reveal a significant enhancement after very short mileage or ash accumulation.

While the increase in filtration with mileage or accumulation of ash is desirable, it does come at the price of an increase in clean pressure drop. This is illustrated in **FIGURE 2** using two examples, one with a coated GPF and one with an uncoated GPF. For both examples a roughly linear increase with ash load can be observed, with the ash load corresponding directly to the mileage. Prior to the pressure drop measurement the filters had been regenerated from any soot present to isolate the effect of ash on pressure drop. It is worth mentioning that the pressure drop in the presence of soot and ash can show a significantly more complex behavior as was observed by Chijiiwa et al. [5]. Understanding what drives the described changes above in filtration and pressure drop performance is of significant practical interest to enable an optimized system and component design.

SOURCES OF ASH

With the change in performance over mileage being attributed to the accumulation of inorganic ash particles, it is important to understand the origin and source of these particles. The analysis of a number of GPFs after extended durability programs has shown that in most cases the majority of inorganic material originates from additives to the lube oils.

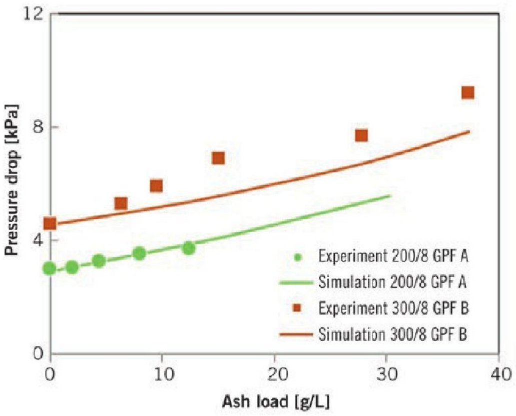

FIGURE 2 Evolution of clean pressure drop as function of ash load, or mileage; data measured on a coated and an uncoated GPF after removal of soot (© Corning)

This is shown in **FIGURE 3**, summarizing the results of a chemical analysis of ash accumulated within GPFs from several durability vehicles. The data shown represents the elemental share of elements associated with three different sources. The largest contribution comes from elements originating from the lubricating oil and potentially the fuel; for example, Ca from detergents, Zn from anti-wear additives like ZDDP and others like P, S, Na and K. Another potential source is catalyst material that originates from an upstream catalyst, for example Al, Si, Mg, Ce, Zr and Ba. The last group has contributions from metal wear or corrosion, usually comprising Fe, Cr and Ni. In inhouse studies the contribution from this last group was the smallest, however, in some other studies significant quantities had been found [6].

With the oil additives representing the largest contribution to ash, the oil consumption and the ash content in the lubricating oil are key parameters to assess and control the accumulation of ash in the GPF. This is analogous to Diesel Particulate Filters (DPF), for which rich experience exists today. For DPF applications it is known that only a fraction, typically 60 to 70 %, of the ash is found in the filter compared to what one would calculate based on the oil consumption and ash content of the oil. The same is true in gasoline applications. However, based on the data available to date, the ash finding rate is lower than for diesel applications. Most of the studies reported show ash masses that are in the range of 10 to 60 % relative to the theoretical value based on the SAPS content of the oil [5]. An alternative approach to estimate the ash mass that can be expected is to evaluate the rate at which ash has been accumulated in mg of ash per km of operation. In recent programs and some literature sources this ash accumulation rate has been on average about 0.17 mg/km (N = 19), with the highest values at slightly above 0.4 mg/km [5].

ASH DEPOSITION AND DISTRIBUTION

To optimize the component design and operation, a detailed knowledge of how ash is collected, where it is deposited, and how it is distributed within the filter is needed to understand the change in filtration behavior described above, as well as, explain the observed pressure drop evolution.

An effective tool to assess the macroscopic and filter scale ash deposition profile are Computed Tomography (CT) scans. In **FIGURE 4** examples of scans taken from 17 filters tested over different mileage on public roads are presented. The mileage is indicated for each filter. CT scans make it possible to look for ash deposition as plugs in the rear of the GPF, with the individual values observed reported in **FIGURE 4**. For most GPFs, no or only very short or localized ash plugs are found, although the measured ash mass suggests that quite some ash had been accumulated. This is different from what is known for DPFs and suggests that ash is also deposited as layer on the channel walls, which cannot be seen in the CT scan due to limitations in resolution. An effective way to assess the ash layer presence and thickness is destructive characterization and careful fracturing of filter segments. An example of this method is shown in **FIGURE 5** together with values for the

FIGURE 3 Ash analysis with respect to the potential source (ash samples N = 6) (© Corning)

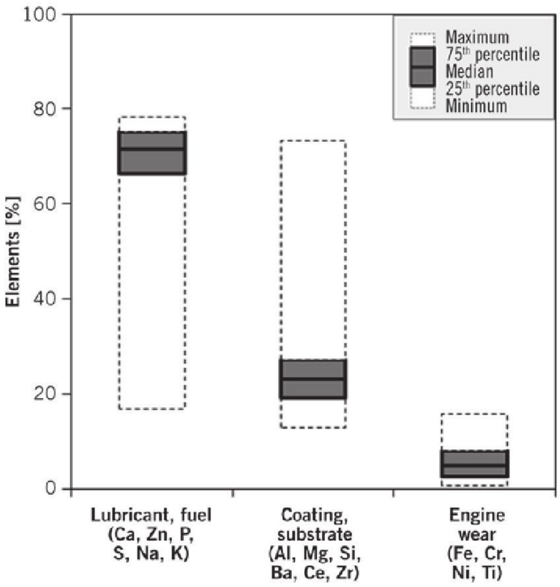

FIGURE 4 CT scan images of GPFs tested on public road over different mileage (note: scale is different for the images) (© Corning)

average ash layer thickness observed as a function of the ash mass found. The error bars indicate the extreme measurements. Chijiiwa et al. [5] had demonstrated that the ash layer typically is relatively uniform within the channel, across the filter, and along the channel length, independent of the ash mass collected. Lines representing correlations that can be used for design purposes are also shown in **FIGURE 5**.

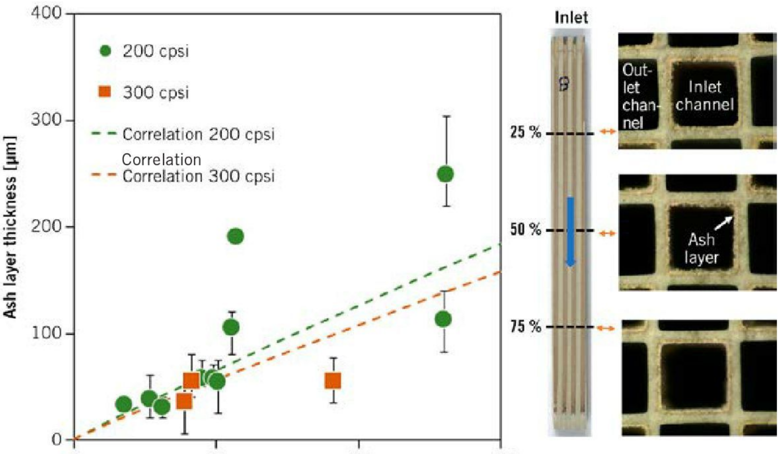

FIGURE 5 Ash layer thickness as a function of the ash mass collected (© Corning)

The observation of ash deposited along the channel walls raises the question of how far the ash is located exclusively as a layer on the channel walls or if it also penetrates into the porous microstructure of the filter wall, changing its permeability. To address this question, **FIGURE 6** (left) shows a Scanning Electron Microscope (SEM) example of a polished cross-section from a GPF operated over high mileage and with high ash load and ash layer thickness. Several observations can be made from this image. First of all, it does seem that there is a fairly sharp separation between the ash layer and porous wall. Almost no ash can be observed inside the pore space. This observation was also made on many other samples characterized. The ash layer itself is characterized by a highly porous structure made up of small particles. In [5] it is stated that the ash consists of small primary particles in the order of 40 to 100 nm which form agglomerates up to a few micrometers. The porous nature of the ash layer is also reflected in the low apparent density, with values in the range of 0.36 ± 0.07 µm and 0.21 ± 0.07 µm in the ash plug and ash layer region [5]. The higher density of the ash plugs is likely explained by the fact that it can contain particles and debris from sources other than oil ash.

The information described above with respect to ash location, ash layer thickness and density can be used in simulations to predict the pressure drop evolution over mileage. Examples of such simulations have been included in **FIGURE 2**. To help explain the change in initial, low mileage filtration efficiency shown in **FIGURE 1**, **FIGURE 6** (right) shows an SEM picture of the filter wall surface. The filter from which the sample had been taken had been operated for only 3000 km. The ash mass accumulated was below the measurement limit, however, filtration efficiency over WLTC increased by about 4 % (absolute). Based on the current understanding, the enhanced filtration is due to ash particles collected preferably in the region of the pore entries, decorating their rims and forming in some cases ash bridges across the pore opening. These ash depositions act as new, efficient collectors, analogous to what has been described by Sanui et al. [7] for soot.

SUMMARY

During operation, gasoline particulate filters collect not only soot but also inorganic ash particles. The collected ash modifies the filtration and pressure drop behavior of the filter, cannot be

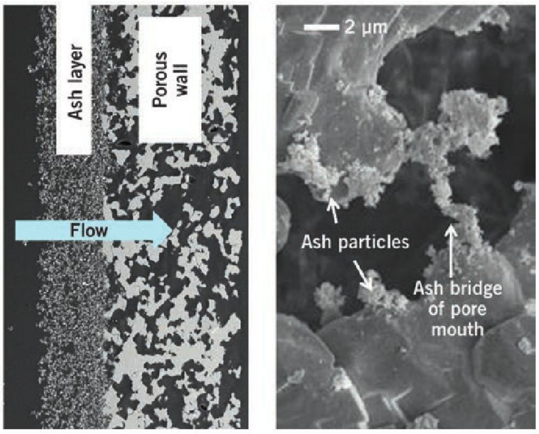

FIGURE 6 SEM image of ash layer on the channel wall after very high mileage (left); initial ash collection after 3000 km at pore entry of channel walls (right) (© Corning)

removed during operation, and is a key focus area in durability studies. While filtration generally benefits from the accumulated ash, the pressure drop without soot increases, which is not desired. It was shown that the behavior can be described by the observation that the ash is collected to a large extent as layer on the channel walls, providing an additional filtration medium, but also increasing the resistance to flow across the wall. The data provided can serve as basis a for design and modeling studies to predict the filter performance over its operation on a vehicle.

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