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Corning Incorporated, Diesel Technologies Development

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# Improved Lifetime Pressure Drop Management for Robust Cordierite (RC) Filters with Asymmetric Cell Technology (ACT)

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## ABSTRACT

The stricter emissions legislation in the US, require the implementation of Diesel Particulate Filters (DPF) for Heavy Duty Diesel engines to meet the 2007 PM emissions targets. Cordierite based wall-flow filters with high filtration efficiency, low $\Delta p$ and good thermal durability are the product of choice for these applications. Continuous passive oxidation of the soot by $NO_2$ is desired, however under certain operating and ambient conditions periodic active oxidation of the soot at elevated temperatures (>550ºC) is required. A part of the PM emissions of the engine contains non-combustible contributions (ashes). These materials accumulate in the filter over lifetime, resulting in an increase in pressure drop as well as a reduction of the filter volume available for soot accumulation. As the pressure drop rises above manageable levels from a performance perspective, ash cleaning of the filter is required. The ash storage capacity of the filter determines the service interval for the filter. Long service intervals are desired by the end customer. To mitigate the impact of the ash accumulation in the filter, Corning Incorporated has developed filters with the proprietary asymmetric cell technology (ACT), providing high ash capacity with good strength attributes. These filters have larger inlet and smaller outlet channels and therefore a higher volume available for ash storage.

The present work summarizes the results of on-engine (HD) ash testing on uncoated Robust Cordierite (RC) filters – Ø267mmX305mm (Ø10.5”x12”) in both Standard (200/19) and ACT (270/16) design configurations. The work demonstrates, for an equal size filter a 30% improved ash storage capacity and therefore longer service interval for the ACT design over the standard filter. Good durability of the filters for a long operation timeframe (up to 2700h) was demonstrated. Furthermore the paper summarizes a wide set of post testing evaluations, both non-destructive and destructive to understand the ash distribution and interactions in the filter.

## INTRODUCTION

Due to their high efficiency, excellent power output and good durability aspects diesel engines have been selected as the most attractive propulsion system in key sectors of the economy. With the increase in fuel costs and further improvements in diesel engine technology the expansion of diesel engine technology in other application segments is anticipated. On the other hand the ever tightening emissions regulations require significant reduction in the tailpipe emissions. For example the US HDD on road emissions legislation requires 90% reduction in PM emissions by 2007(relative to 2006 PM limits) and 80% reduction in NOx by 2010 (relative to 2009 NOx limits). The lower emissions are achieved by improvements in engine technology and the use of advanced emissions technologies. Diesel Particulate filters are required for achieving the low PM emissions levels to meet the 2007 US on-road regulations. It is expected that the 2010 NOx limits will be achieved by further advancements in engine technology, improved controls and implementation of DeNOx technology - in the form of Selective Catalytic Reduction (SCR) system or Lean NOx Traps (LNT) or a combination of both.

Cordierite wall flow monoliths have emerged as the choice of the industry for use as diesel particulate filters (DPFs) due to their compactness and robust design.

The design of diesel particulate emissions systems requires balancing of various competing constraints. On the one hand the soot capacity of the filter needs to be sufficiently high to enable the desired regeneration intervals. The soot capacity is driven by the filter volume, the regeneration conditions and control strategy. On the other hand engine back pressure needs to be managed. This includes management of clean and life-time pressure drop for optimized performance of the engine. Corning’s Robust Cordierite (RC) material was developed for medium and heavy duty OEMs and retrofit applications. It provides good soot loading capacity, low pressure drop and excellent durability and strength.

The non-combustible part of the PM generally known as ash accumulates in the filter resulting in increased backpressure on the engine. This increased back pressure leads to higher fuel consumption, lower power output/dynamic response and lower heat rejection to the exhaust. Furthermore adverse effects on engine durability are expected. Increased amounts of ash in the filter, lowers the soot capacity of the filter and thereby requiring frequent regenerations.

Ash in diesel particulate filters typically consists of sulfates, phosphates, or other oxides of calcium, zinc, magnesium, and other metals that are formed in the engine's combustion chamber from burning of additives in the lubricating oil and fuel. These additives are present in the engine lubricating oil as detergents, dispersants, acid neutralizers, anti-oxidants, corrosion and rust inhibitors, anti-wear and extreme pressure additives, etc. The ash also contains metal oxide impurities resulting from wear of the engine that are carried into the combustion chambers by the lubricating oil. The ash sometimes includes oxides of iron, copper, chromium and aluminum formed from the corrosion of the exhaust system components upstream of the DPF [1].

The composition of ash depends on various factors such as the engine type and runtime, driving conditions, type of fuel, fuel additives, motor oil additives, and metallurgy of the exhaust system.

The impact of ash can be mitigated by optimization of filter design parameters (geometry) and/or by periodic ash cleaning. Corning Incorporated introduced the asymmetric cell technology (ACT) design for DPFs to reduce the impact of ash on performance [2].

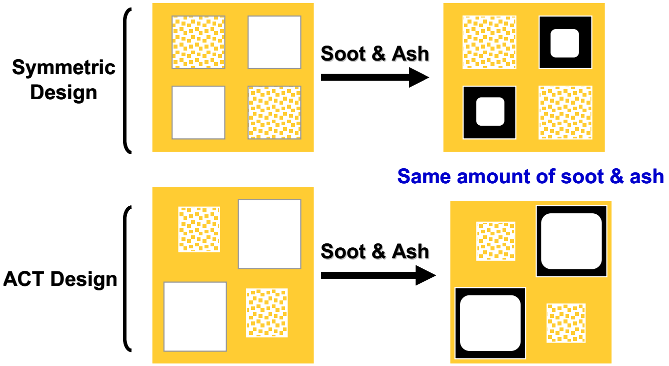


**Figure 1. Standard and Asymmetric Cell Technology (ACT) Designs**

The ACT channel design has larger inlet channel volume for improved ash storage capacity. Corning Incorporated's Robust Cordierite (RC) 270/16 ACT has the same bulk heat capacity as Robust Cordierite (RC) 200/19 (standard design). Hence both designs have similar thermal regeneration response. They have similar physical properties and hence similar mechanical and thermo-mechanical durability performance. Robust Cordierite (RC) ACT 270/16 offers better ash storage capacity than Robust Cordierite (RC) 200/19 (standard design) due the larger inlet volume and reduced wall thickness at the same time offering the excellent regeneration performance similar to Robust Cordierite (RC) 200/19 (standard design).

Figure 2 illustrates the relationship between ash cleaning interval (DPF pressure drop limited) and filter volume for standard and ACT designs. A significant increase in ash cleaning service interval at a constant filter volume is enabled by the use of ACT design over standard. On the other hand the filter volume can be reduced by use of the ACT design for a fixed DPF ash cleaning interval/Δp limit.

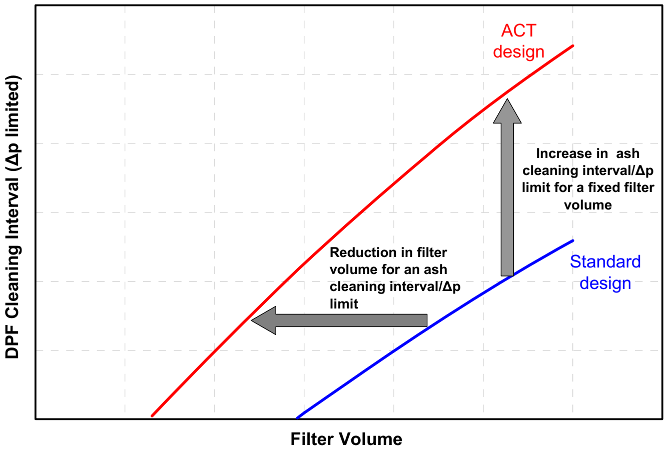


**Figure 2. DPF service interval as a function of filter volume (at constant porosity and pore structure)**

The objectives of this program were to characterize the pressure drop of Robust Cordierite (RC) filters (200/19-standard & 270/16 ACT design) with on-engine ash accumulation and to demonstrate the performance benefit of ACT design. Furthermore we evaluated the impact of long term engine exposure on material durability.

## MATERIALS AND EXPERIMENTAL SET-UP

Two uncoated Robust Cordierite (RC) filters Ø267mmX305mm (Ø10.5"x12") (17literes) were tested for this ash durability study. The attributes of the filters are summarized in Table 1.

**Table 1. Attributes of filters tested (Nominal values)**

| Property | RC | RC ACT* |
|---|---|---|
| Dimesnsions | **Ø267mmx305mm**<br>(Ø10.5"x12") | **Ø267mmx305mm**<br>(Ø10.5"x12") |
| Cell density (cpsi) | 200 | 270 |
| Wall thickness (mils) | 19 | 16 |
| Inlet channel diameter (mm) | 1.35 | 1.29 |
| Outlet channel diameter (mm) | 1.35 | 0.97 |
| Inlet open frontal area (%) | 27 | 34 |
| Filter Volume (l) | 17.0 | 17.0 |

*ACT - Asymmetric Cell Technology

Both the filters were similar in material composition and microstructure but, were of different geometric configurations. The standard design filter had 200cells/in² where as the ACT design filter had 270 cells/in². One of the filters was a standard design (equal inlet and outlet channel hydraulic diameters) and the other was an ACT design (inlet channel hydraulic diameter greater than outlet channel hydraulic diameter). The walls of the ACT design filter were thinner than that of the standard design filter. The geometric design of the ACT filter results in a 25% increase in inlet channel volume.

This ash durability testing was performed in two test cells with two heavy duty engines – Ash accumulation test cell and characterization test cell.

## ASH ACCUMULATION TEST CELL

A Cummins N14 engine was used for accumulating ash into the filters. In the beginning of the program it was decided to use a separate engine for ash loading, as the ash engine would be subjected to higher back pressures as the filters reached higher ash levels. The specifications of the ash accumulation engine are shown in Table 2.

**Table 2. Ash accumulation Engine Specifications**

| Ash Accumulation Engine Specifications (Cummins N14) | |
|---|---|
| Number of Cylinders | 6 |
| Cylinders Configuration | Inline |
| Model Year | 1992 |
| Displacement Volume | 14 Liters |
| Rated Power | 343 kW @1800RPM |
| Torque @ Rated | 1763N-m |
| Peak Torque | 2034N-m @1400RPM |

The ash engine was connected to a wet gap eddy current dynamometer. The capacity of the dynamometer was 650HP (max. power it is designed to absorb) when operated within the speeds of 1200 to 4000 RPM. The ash loading test cell was equipped with three UEGO sensors (for measuring engine-out oxygen, oxygen before the filter and oxygen after the filter). It was also equipped with an engine-out $NO_X$ sensor. The ash loading test cell also had a custom designed oil reservoir/weight load cell for real–time monitoring of oil consumption. Differential pressure sensors were installed across the filter and 400cpsi/7mil DOC (Ø267mmx152.4mm). Additional instrumentation was installed in the ash accumulation test cell to measure intake air mass flow, accelerator pedal position, absolute pressure and temperatures at various locations in the exhaust system and aftertreatment system.

In the ash accumulation cell the crankcase gases (blowby) were recirculated back into the intake.

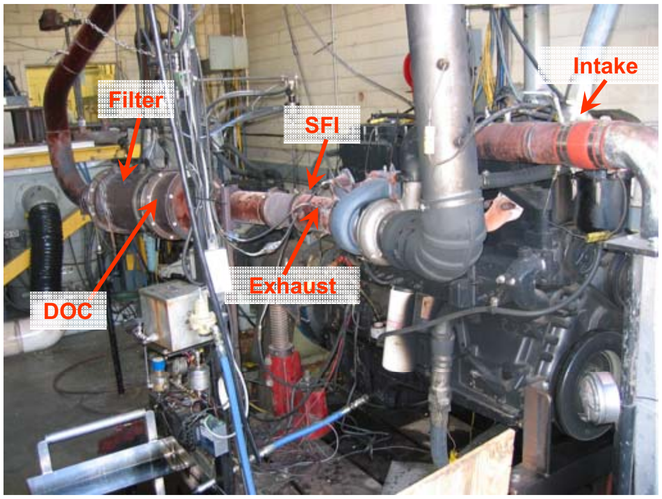


**Figure 3. Ash accumulation test cell set-up**

## CHARACTERIZATION TEST CELL

The characterization test cell was used for the evaluation and characterization of the ash loaded filters. Pressure drop measurements, soot loading and controlled regenerations (soot cleanouts) were performed in this test cell. A Volvo D12 engine was used as the characterization engine. Table 3 lists the specifications of the characterization engine.

**Table 3. Characterization Engine specifications**

| Characterization Engine Specifications (Volvo VE D12 ) | |
|---|---|
| Number of Cylinders | 6 |
| Cylinders Configuration | Inline |
| Model Year | 2003 |
| Displacement Volume | 12 Liters |
| Rated Power | 347kW @1800RPM |
| Torque @ Rated | 1898 N-m |
| Peak Torque | 2237N-m @1200RPM |

The Volvo D12 Engine was connected to an eddy current dynamometer. The capacity of the dynamometer was 500HP (max. power it is designed to absorb) when operated within the speeds of 1250 to 4000 RPM. The characterization test cell was instrumented with three oxygen sensors to measure engine-out, filter upstream and filters downstream oxygen concentration. The oxygen sensors enabled the measurement of dynamic changes in the oxygen concentration of the exhaust. The characterization test cell was equipped with full raw-emissions sampling bench consisting of a pair of $O_2$, HC, Low CO, High CO, $CO_2$ analyzers upstream and downstream of the filter and an engine-out NOx sensor. The characterization test cell was also equipped with additional instruments for measuring pressure and temperature at various locations in the exhaust system and aftertreatment system. A smoke meter is installed downstream of the filter to measure smoke number at various stages of the testing.

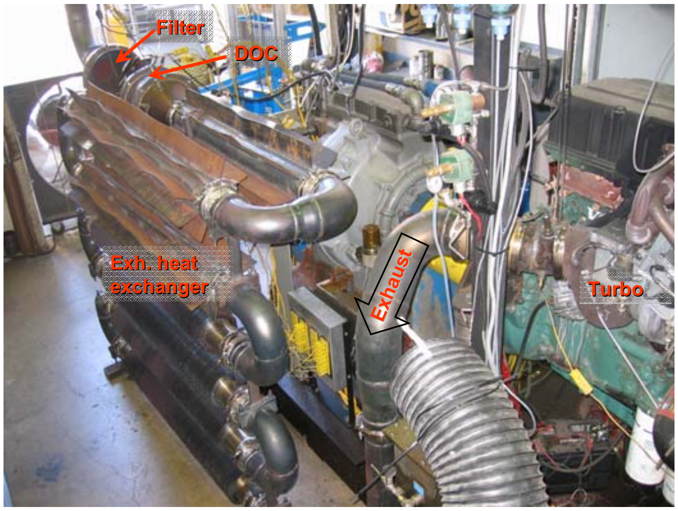


**Figure 4. Characterization test cell set-up**

As can be observed, a bank of heat exchanger tubes were installed in the exhaust line with a bypass valve. The purpose of this heat exchanger was to decrease the temperature of the exhaust going into the filter in order to avoid the possibility of soot combustion during pressure drop characterizations.

Supplemental Fuel Injection (SFI) system

A supplemental fuel injection (SFI) system was installed in front of the diesel oxidation catalyst (DOC) for fuel dosing into the exhaust. It was custom designed system using an Accel gasoline port fuel injector with a maximum fuel rate of 16.33 kg/hr (36 lbs/hr) and a nominal operating pressure of 45 psi. The configuration of the system is shown in figure 5.

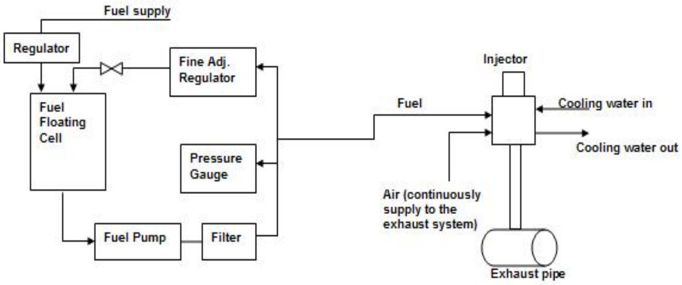


**Figure 5. SFI System-layout**

Fuel specifications

Ultra low sulfur diesel (ULSD) fuel was used throughout the testing on both the characterization and the ash loading engine. Specifications of the USLD fuel used for the testing program are summarized in Table 4.

**Table 4. Specification of the fuel used**

**Ultra Low Sulfur Diesel Fuel Properties**

| Property | ASTM | Results |
|---|---|---|
| Flash Point, °C | D93 | 84.5 |
| Cloud Point, °C | D2500 | -22.23 |
| Pour Point, °C | D97 | -28.9 |
| Gravity@60°C, API | D4052 | 37.03 |
| Viscosity, cSt@40°C | D445 | 2.86 |
| Saybolt Color | D156 | 17 |
| Distillation | D86 | |
| IBP, °C | | 211.7 |
| 10% Recovery Point | | 446 |
| 50% Recovery Point | | 506 |
| 90% Recovery Point | | 590 |
| FPB, °C | | 332.8 |
| Carbon Residue, mass fraction | D524 | 0.004 |
| Lubricity, HFRR,µm | D6079 | 476 |
| Acid Number | D974 | 0.0053 |
| Corrosion, Copper Strip | D130 | 1A |
| Aromatic Content, % mass | | 7.62 |
| Sulfur, ppm | D6428 | 0.81 |
| Sulfur, wt% | D6428 | 0.00008 |
| Cetane Index | D4737 | 49 |

The values shown in the table are for only one specific fuel batch received. The fuel used met all the specifications outlined on the fuel analysis report, but values varied within the allowable ranges (sometimes significantly – such as fuel sulfur level varying from 0.5ppm to 12ppm).

Engine Lubricating oil specifications

The lubricating oil used for the ash testing was custom blended for research purpose. The following table summarizes the important specifications of the lubricating oil from ash testing perspective.

**Table 5. Engine Lubricating Oil Analysis Results**

**Ash Testing Lube Oil Analysis [Fresh]**

| Description | ASTM | Results |
|---|---|---|
| Metal Analysis, ppm | | |
| Al | D5158 | 2 |
| Sb | | 2 |
| Ba,Cu,Cr,Pb,Mn | | <1 |
| Mo,Ni,Ag,V,Ti,Cd | | <1 |
| B | | 463 |
| Ca | | 4136 |
| Fe | | 3 |
| Mg | | 923 |
| P | | 1273 |
| Si | | 9 |
| Na | | 6 |
| Sn | | 5 |
| Zn | | 1421 |
| K | | <5 |
| Sr | | 2 |
| Ash Content, mass % | D482 | 1.69 |
| Sulfur Content, wt% | D4951 | 0.921 |
| Sulfur Content, ppm | D4951 | 9205 |
| Viscosity | D445 | |
| @ 40°C, cSt | | 14.43 |
| @ 100°C, cSt | | 111.5 |
| NOACK, wt % | D5800 | 16.8 |
| CCS @20°C, wt % | D5923 | 5424 |

## TESTING METHODOLOGY

Initially a thorough baseline of the clean $\Delta p$ was demonstrated with multiple tests. Furthermore the initial clean weights were determined repeatedly.

This was followed by a ash accumulation testing consisting of the following phases –

- Ash accumulation in the filter to next ash load target (Ash accumulation test cell)
- On-engine DPF soot cleanout/controlled regeneration (Ash accumulation test cell)
- Filter weighting to determine the ash load
- Pressure drop characterization phase with repeats to obtain good confidence on results (Characterization test cell)
- On-engine DPF soot cleanout/controlled regeneration (characterization test cell)
- Filter weighting to confirm the ash load

For accelerated ash accumulation low DPF-volume/engine-power-output along with a high load profile cycle was used. The cycle used for ash accumulation was a custom developed cycle as shown in Figure 6.

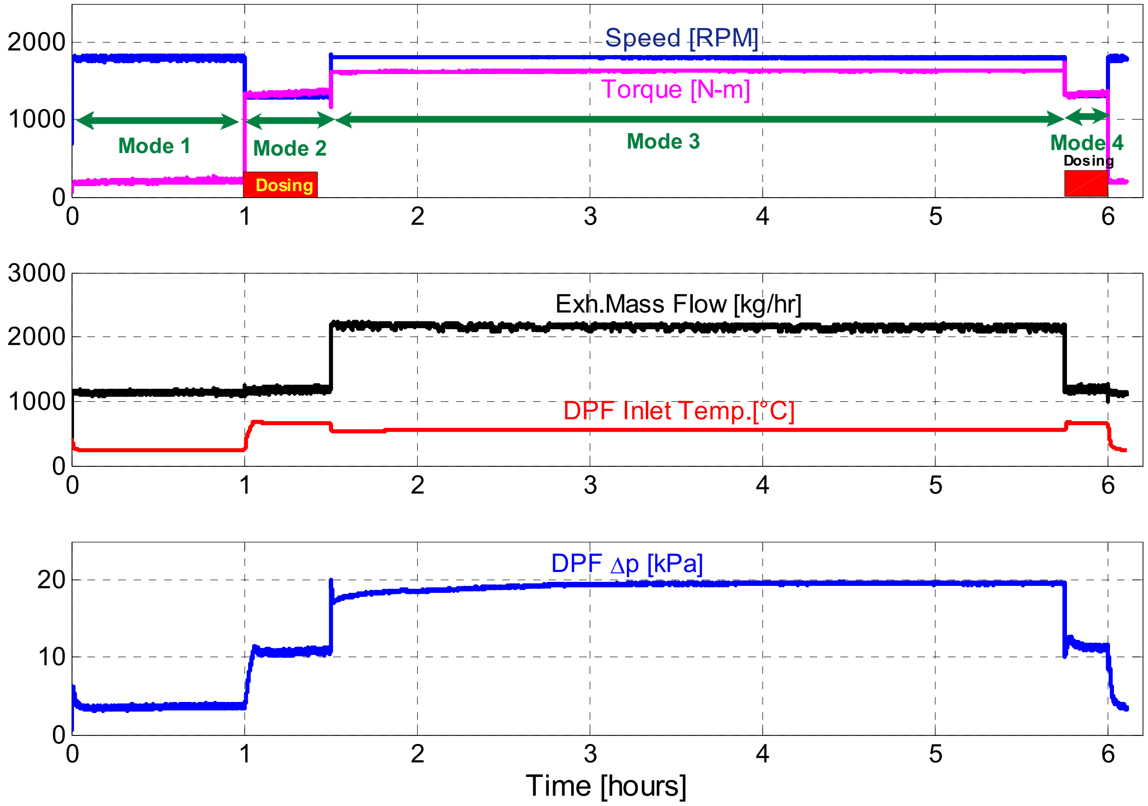


Figure 6. Ash accumulation cycle

The ash accumulation cycle was 6 hours in duration with four modes of operation. The mode 1 of the cycle represents the low load operation of the engine with some soot accumulation. Mode 2 represents controlled active regeneration of the filter. Mode 3 represents rated operation of the engine, during which the filter is in passive regeneration mode. And finally mode 4 represents 15 minutes of active regeneration following the passive regeneration (mode 3).

**Table 6. Ash accumulation cycle - operating points**

| Ash Cycle | | | |
|---|---|---|---|
| | Speed | Load | SFI* |
| | RPM | N-m [lb-ft] | |
| Mode 1 | 1800 | 203 [150] | OFF |
| Mode 2 | 1300 | 1356 [1000] | ON |
| Mode 3 | 1800 | 1627 [1200] | OFF |
| Mode 4 | 1300 | 1356 [1000] | ON |

* SFI - Supplemental Fuel Injection

The accumulation cycle was developed such that over 70% of the ash accumulation cycle time is in mode 3 since maximum lube oil consumption was found to be in mode 3. This resulted in a high load profile cycle with average load factor 0.74.

Clean-outs on the filter were performed in two stages for complete soot removal. During cleanouts filter inlet temperature was gradually increased to 650°C by incremental dosing of fuel into the exhaust. The filter inlet temperature was maintained above 650°C for over 15 minutes and smoke numbers were recorded during this phase, downstream of the filter. The mass flow during cleanout was maintained at 950kg/hr.

The accelerated soot loading into the filter was performed at a steady operating point (with EGR). The soot loading point (RPM; lb-ft) was chosen such that the engine generated significant amount of soot and the nature of the soot was not different from that generated during normal engine operation. Before beginning the program validation experiments were performed to warrant representative soot loading and uniform soot distribution in the filter. Passive soot regeneration during loading was prevented by managing temperature, $NO_2$ and $O_2$.

The pressure drop characterization measurements were performed at 0g/l, 3g/l and 6 g/l soot loadings in the filter. The soot loading in the filter was cumulative (0g/l → 3g/l → 6g/l) without performing regenerations in-between. Pressure drop characterization at each soot load was performed at various combination of engine operating speeds and low loads encompassing the entire operating flow range of the engine. During the pressure drop characterization test the filter inlet temperature was maintained below 250°C to passive soot oxidation. The pressure drop test consists of 5 different steps encompassing the normal operating flow range of the engine with each step 3 minutes in duration. It also contains two back check points to indicate, if there was any soot accumulation or oxidation during a pressure drop test as shown in figure 7.

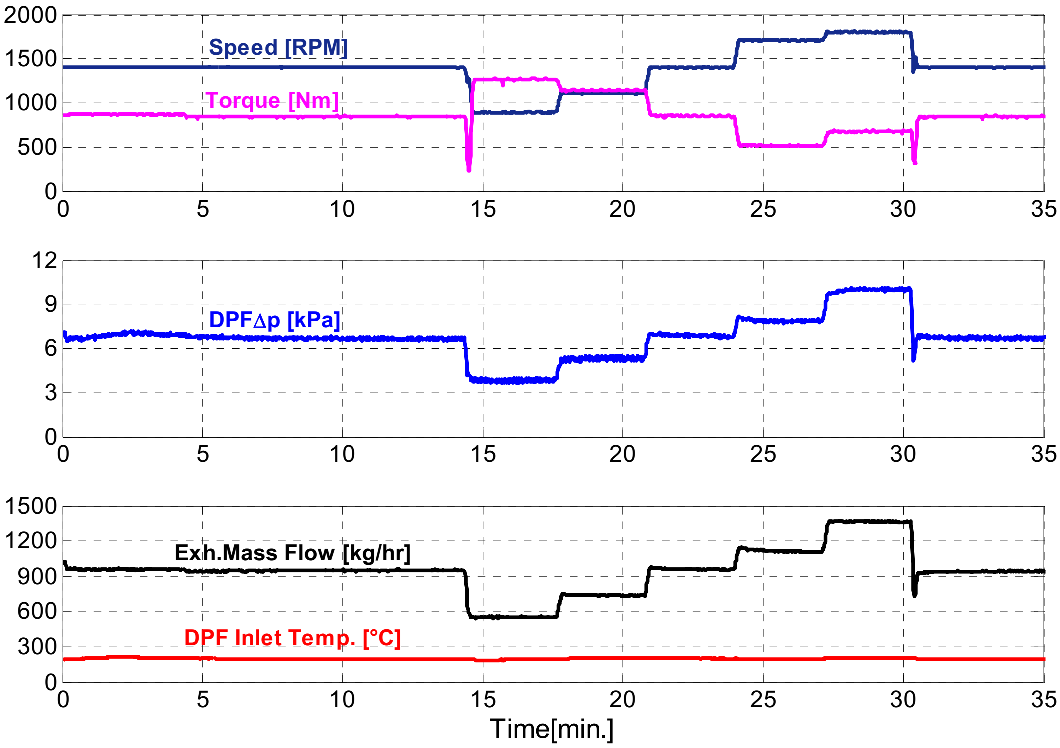


**Figure 7. Pressure drop characterization test (at a soot load)**

After the pressure drop characterization test at 6g/l the filter was cleaned (on-engine) and a repeat of the pressure drop characterization test with no soot was performed to check repeatability of the pressure drop measurement.

Initially the filters were characterized for pressure drop with small ash increments to capture the conditioning effect observed at small ash levels. As the testing progressed the pressure drop characterization ash increment was increased. Reference filters were tested at various intervals during the program to make sure that the testing conditions did not change.

The oil consumption was measured by a conventional drain-and-weigh method. The initial oil change was determined by a start-of-test oil drain. The oil was returned to the engine after weighting. Pre-weighed amount of fresh oil was added to make up for the oil consumed. After every 500 engine hours the oil was drained, weighed and discarded. And the used oil was replaced with fresh oil.

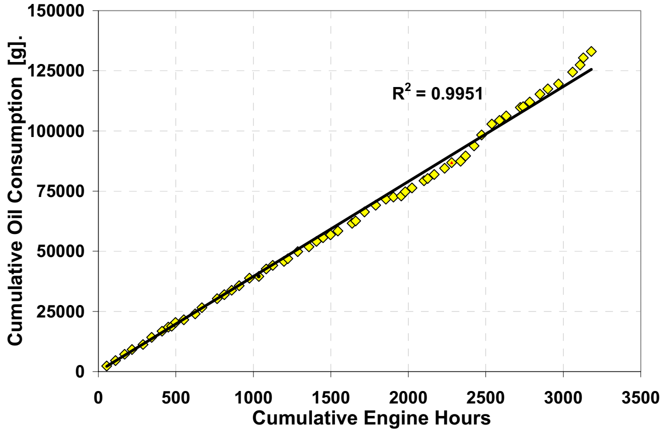


**Figure 8. Variation of Oil consumption with engine hours - Ash accumulation engine (Cumulative)**

The average ash content of the custom blended lubricating oil used for this testing was 1.69 mass% determined by ASTM D482 method. The mass of ash formed during each test interval was determined by weighing the DPF at the beginning and end of the ash interval. The DPF was thermally regenerated (on engine) before weighing, such that no soot was left in the DPF, and the weight increase was purely attributed to ash accumulation. The oil consumption of the ash accumulation engine during the test program was constant as shown in figure 8.

## RESULTS AND DISCUSSION

### OIL CONSUMPTION AND ASH ACCUMULATION

The amount of ash accumulating in the diesel particulate filter (DPF) strongly correlates to the engine lube oil consumption (Figure 9) which is in line with other studies [3,4].

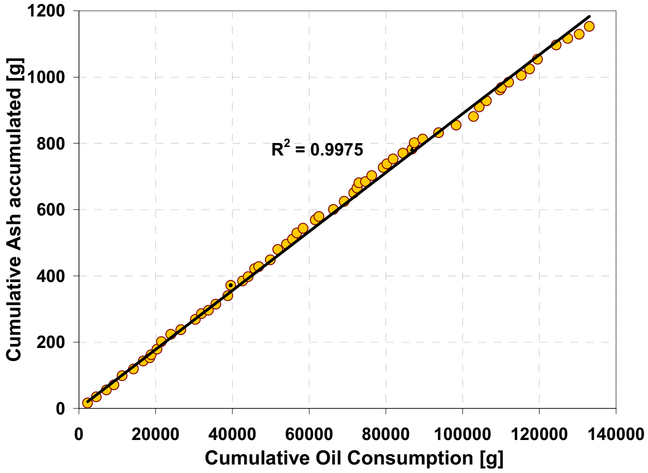


**Figure 9. Cumulative Ash accumulation linearly correlates to Cumulative oil consumption**

The ash finding rate in the DPF based on 1.69 wt% ash content lube oil was 55-60% which is marginally lower than expected. In order to further investigate the lower ash finding rate in the DPF, samples of fresh and used (500 engine hours) lube oils were analyzed and the results are depicted in Figure 10.

The ash components (i.e. Ca, Mg, Zn, etc.) contained in the lube oil additives tend to concentrate in the used oil as lighter hydrocarbon constituents of the base oil volatilize at a faster rate. Consequently the ash finding rate in the filter is lower than expected based on oil consumption inline with other studies [4,5].

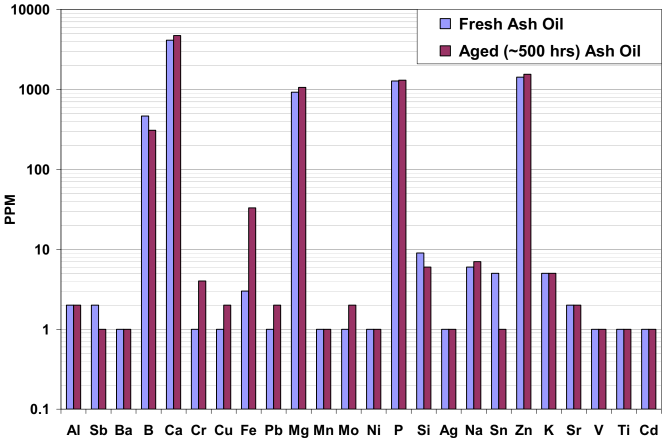


**Figure 10. Comparison of Fresh and used lube oil elemental composition**

Hence it is postulated that the low ash finding rate in the DPFs could be attributed to two main reasons – Firstly ash forming metals (i.e. Ca, Mg, Zn, etc) do not volatilize at the same rate as lighter base oil species and secondly a fraction of the metals lost from the bulk oil, deposit on engine and after-treatment system components upstream of the filter [4].

## PRESSURE DROP

The pressure drop across a wall flow monolith DPF can be classified into five major components – Inlet contraction losses, frictional losses along inlet channel walls, frictional losses from flow through walls, soot & ash layers, and frictional losses along outlet channel walls and finally outlet expansion losses. The percentage contribution of each of these components to the total pressure drop varies significantly with the state of the filter. The contraction and expansion losses are significant when the filter is in a clean state. As the filter accumulates soot and ash, the wall (including soot & ash layer) flow resistance dominates.

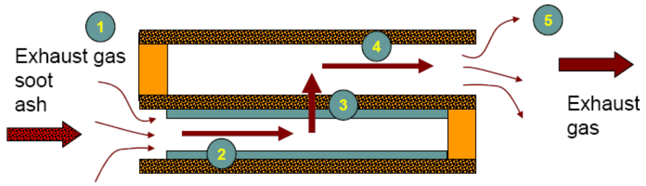


**Figure 11. DPF (wall flow monolith) Pressure Drop Contributers**

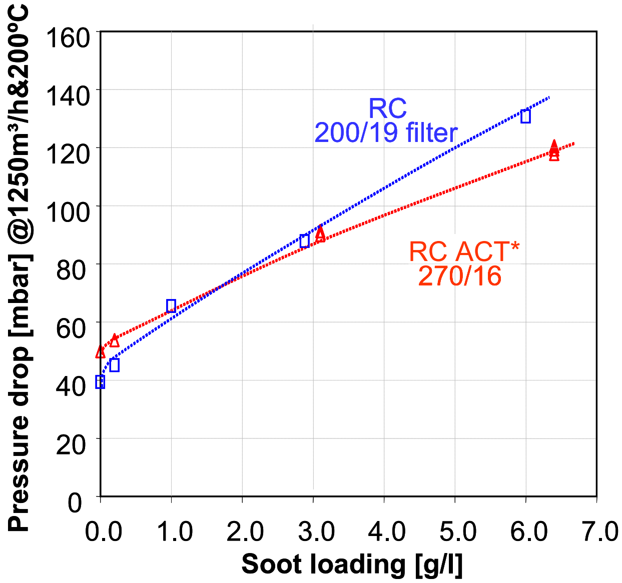


**Figure 12. Pressure drop (normalized) variation with soot load (without Ash in filters)**

Figure 12 depicts the normalized pressure drop variation with soot load for both the filters. It can be observed that in clean soot (No Ash & No soot), the ACT filter exhibits slightly higher pressure drop due to the narrower outlet channels. As the filters accumulate soot the pressure drop increases faster for standard design filter compared to ACT filter, which can be observed by comparing the slopes of the two curves in figure 12. The ACT design filter exhibits significantly lower pressure drop at 6g/l soot than the standard design filter.

Figure 13 illustrates the pressure drop variation with flow rate at 0g/l and 6g/l soot loads over the normal operating flow rates with no ash in the filters. It can be observed that over the normal operating flow range the ACT design filter exhibits slightly higher pressure drop in the absences of soot and ash in the filter. The soot loaded pressured drop at 6g/l is slightly lower for ACT design filter than standard design filter.

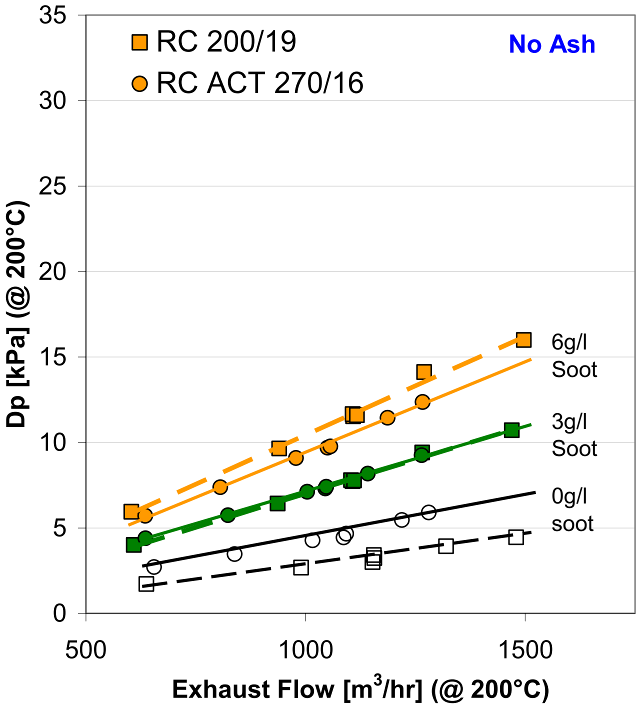


**Figure 13. Pressure Drop variation with exhaust Flow (normalized for temperature) - with No Ash**

The filters were tested with incremental ash loading until a pressure drop limit of ~250 mbar (at 1250m³/hr flow and 200°C temperature) was reached at 6g/l soot load. Any significant increase in pressure drop beyond this range would have a significant backpressure on the engine thereby significantly impacting the normal operation of the engine. This pressure drop limit was reached for the standard filter at 680g of ash and for the ACT filter at 929 g of ash.

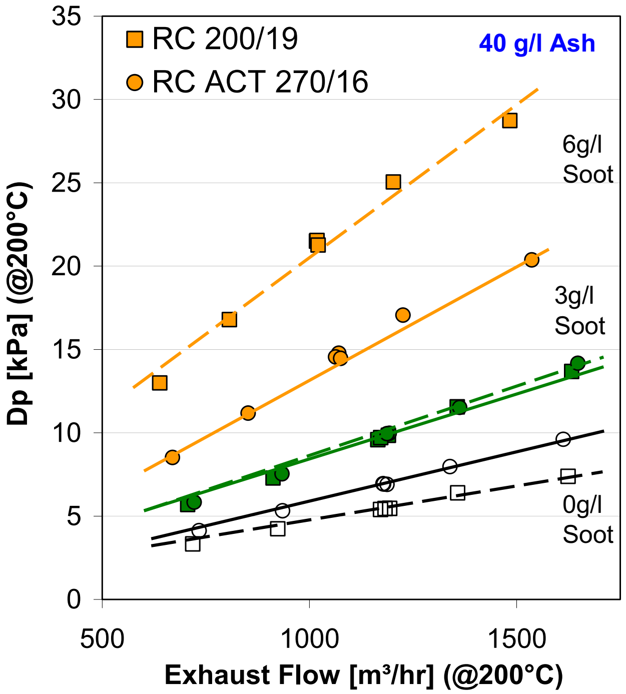


**Figure 14. Pressure Drop variation with exhaust flow (temperature normalized) - with 40g/l (680g) Ash**

At increased ash and soot load levels in the filter the ACT design exhibits significantly lower pressure drop (Figure 14).

Figure 15 illustrates the pressure drop (normalized) development with increasing ash load in the filter. For all ash loads and without soot in the filter the ACT design filter exhibits slightly higher pressured drop. This is attributed to the higher cell density and the smaller exit channels. The soot loaded pressure drop for ACT design filter at 6g/l soot is significantly lower than that for the standard design filter, at all ash levels. The soot loaded pressure drop dependent on the ash load level in the filter can be separated into three major phases (Figure 15) – Initially at low ash loads in the filter the pressure drop decreases before its starts increasing. This happens due to the formation of a thin ash membrane on the filter inlet walls (at low ash levels), that prevents the deep bed penetration of soot into filter walls, thereby decreasing the effective resistance of the walls as compared to the no ash condition. This is followed by a phase in which the pressure drop increases linearly with increasing ash mass in the filter. This is due to reduction in effective filter inlet channel volume due to increasing space occupied by ash. And finally the pressure drop increases significantly with a small increment in ash load. In this phase the effective inlet channel hydraulic diameter decreases due to the presence of thick ash and soot layers (same amount of soot packs into a smaller effective channel volume due to increased ash content) on the inlet channel walls. If possible it is preferable to avoid the last phase from occurring in real life on-vehicle application of DPF. Since in this phase the pressure drop increases significantly with small increase in soot load thereby resulting in increased regeneration frequency and higher fuel consumption.

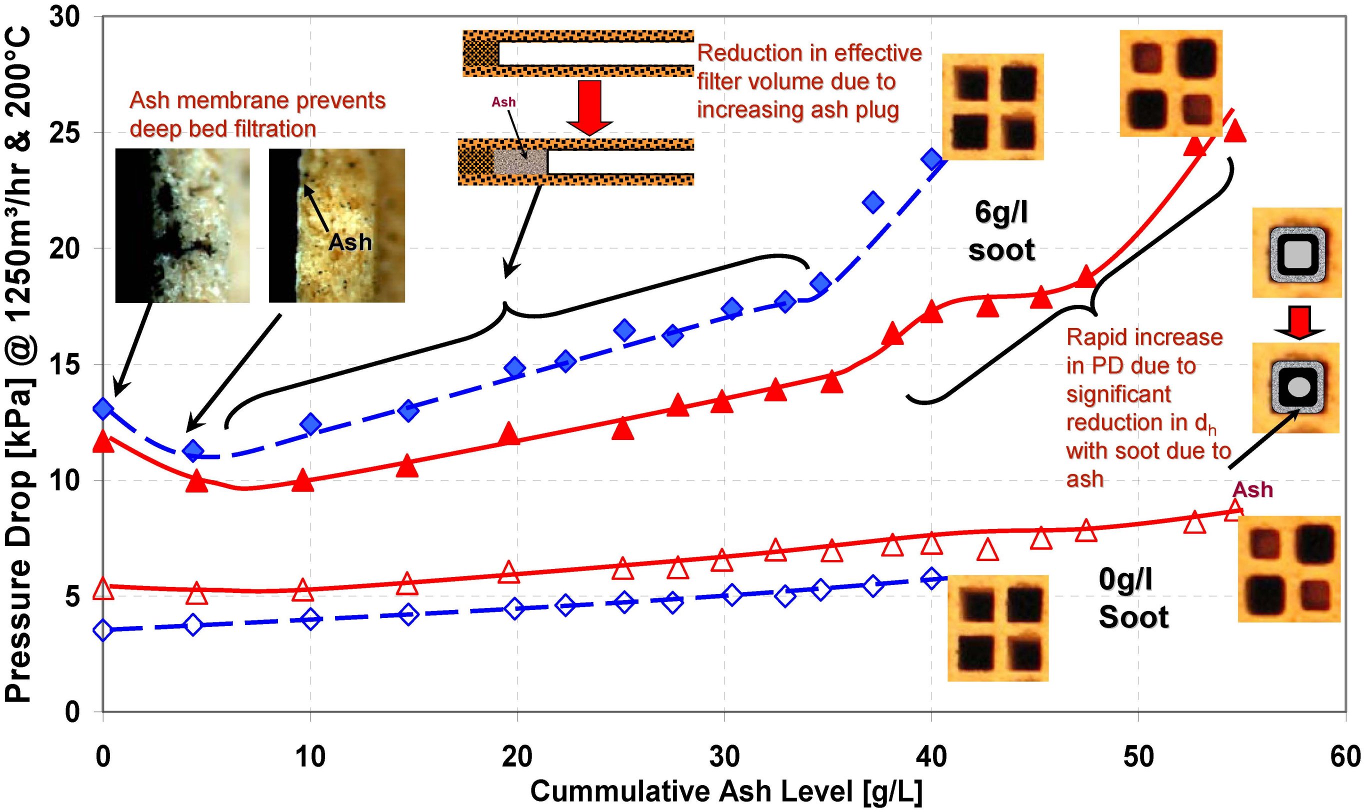


**Figure 15. Pressure Drop (normalized) variation with ash mass in filter**

Over the entire duration of the testing program, the pressure drop during the ash accumulation phases was monitored continuously. Figure 16 illustrates the average pressure drop as recorded during each of the ash accumulation cycle modes for the Robust Cordierite (RC) ACT 270/16 filter. It can be observed that initially the pressure drop increases moderately followed by a pronounced increase at higher ash cycle numbers.

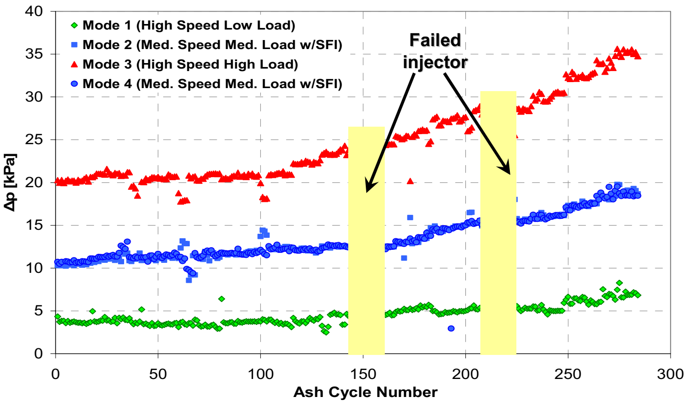


**Figure 16. Pressure drop development with ash accumulation for RC 200/19 (Ash Accumulation Engine)**

THERMAL EXPOSURE

Figure 17 illustrates the time spent by each of the filter in each 100°C temperature interval during the testing program. The ACT filter spent over 60% of its time 500-700°C temperature interval whereas the standard filter spent over 65% of its time in 500-700°C temperature interval.

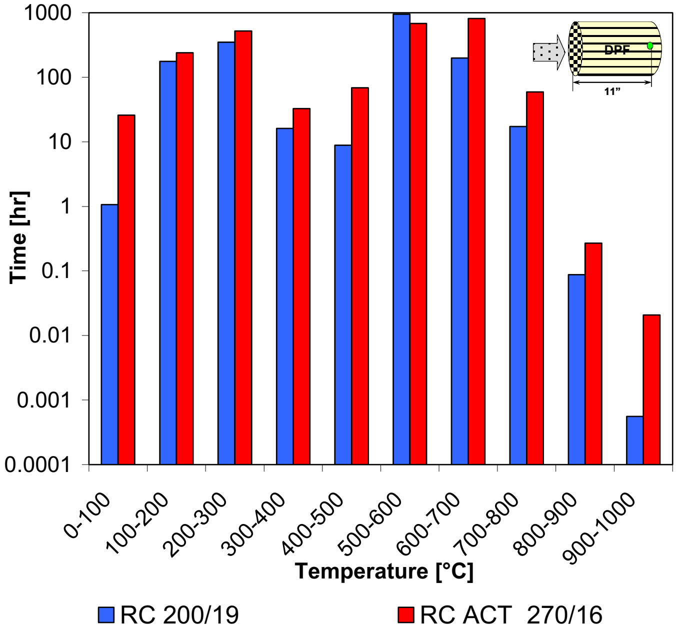


**Figure 17. Lifetime Time- Temperature distribution**

The Robust Cordierite (RC) 200/19 filter was on-engine test for over 1700 hours during the testing, equivalent to the number of regenerations experienced in 300k miles. The Robust Cordierite (RC) ACT 270/17 filter was tested over 2600 hours, with a regeneration equivalent of 450k miles. The peak recorded temperatures on the standard design and ACT design filters were 908°C and 968°C respectively. The high temperatures were experienced during intentionally introduced uncontrolled regenerations.

FILTRATION PERFORMANCE

Both the filters exhibited excellent initial filtration performance, which further improved with ash accumulation/conditioning. The filters did not show any degradation in filtration performance at any stage during the testing.

At the end of the ash testing program steady state ramped-modal tests [6] were performed on the Robust Cordierite (RC) ACT 270/16 filter to evaluate the emissions compliance of the filter. A test sequence of three tests was repeated three times. The filter exhibited a maximum PM emission of 0.56mg/kW-hr, when the 2007 emissions compliance limit is 13.4mg/kW-hr.

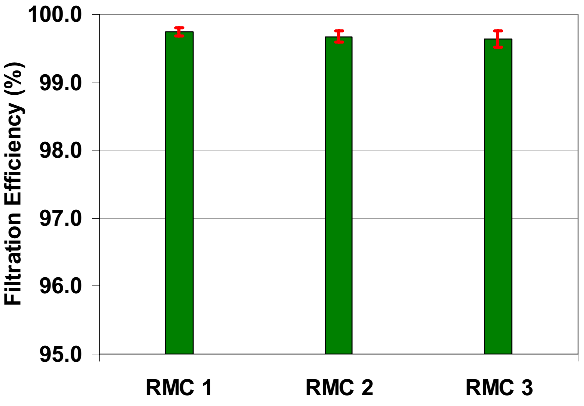


**Figure 18. Filtration Efficiency during Ramped Modal Cycle (RMC) Testing**

The Robust Cordierite (RC) ACT 270/16 filter showed excellent PM filtration efficiency for all tests as summarized in Figure 18.

POST TEST ANALYSIS

After test the filters were de-canned and inspected for integrity. Both the filters did not show any degradation based on CT (Computer Tomography) scanning and visual observations, inline with the good filtration performance.

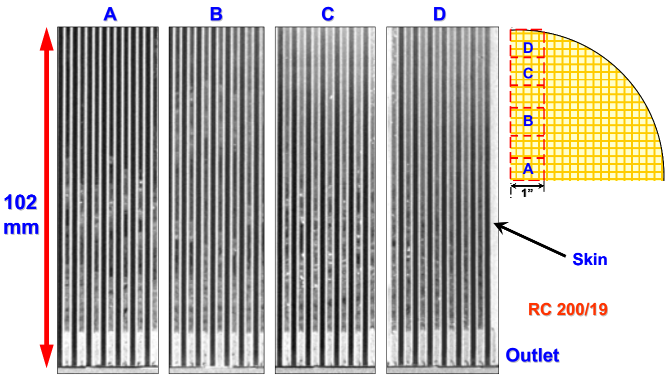


**Figure 19. Ash distribution at various locations for RC 200/19 (Computer Tomography-scanning Images)**

Figure 19 shows the ash distribution at various locations in the filter as evaluated by CT scan. Large high density ash-plugs are separated by voids/low density ash pockets.

A high density ash layer was observed on the inlet channel walls as shown in figure 20. The thickness of the high density ash layer increased from inlet to outlet. Large low density ash in the form of an ash-plug was found near the outlet. This phenomenon was observed in both the filters at corresponding locations.

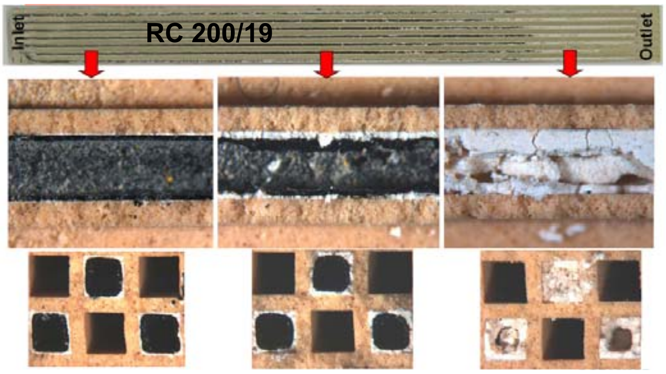


**Figure 20. Ash and soot distribution along a channel**

The length of the ash plug (near outlet) decreased from center to skin as illustrated in figure 21 for the Robust Cordierite (RC) ACT 270/16..The ash accumulation was higher in the center of the filter than in the periphery due to increased mass flow through the center and continued further predominantly due to inertial deposition. Similar ash distribution profile was also observed for the Robust Cordierite (RC) 200/19 filter. The absolute length of the ash plugs was different for the two filters due to lower quantity of ash in the Robust Cordierite (RC) 200/19 filter than in RC ACT 270/16 filter.

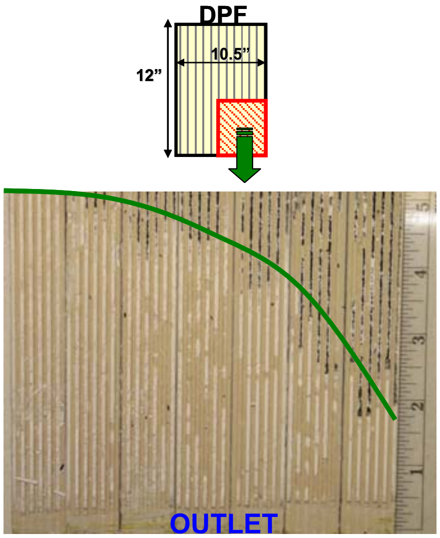


**Figure 21. Ash-plug variation from center to skin (Robust Cordierite (RC) ACT 270/16)**

Other studies [7] have indicated that ash deposition in DPFs occurs in two modes based on factors like mode of operation of engine, type of regeneration etc. during ash accumulation. The ash predominantly deposits on the surface walls of the filter, if the ash accumulation is performed under continuous regeneration at high loads. In the case of ash accumulation under low load operation with active or stochastic regeneration, significant amount of ash ends up in the form of an ash-plug towards the rear end of the filter. The cycle used for ash accumulation in this study consists of both high load and low load operation along with passive and active regeneration. The ash distribution in both the filters was a combination of ash on walls & ash plug near outlet as expected.

No preferential separation of certain ash components is apparent as illustrated in figure 22.

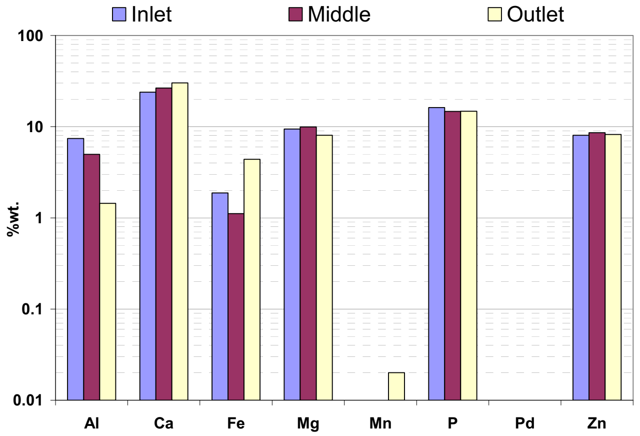
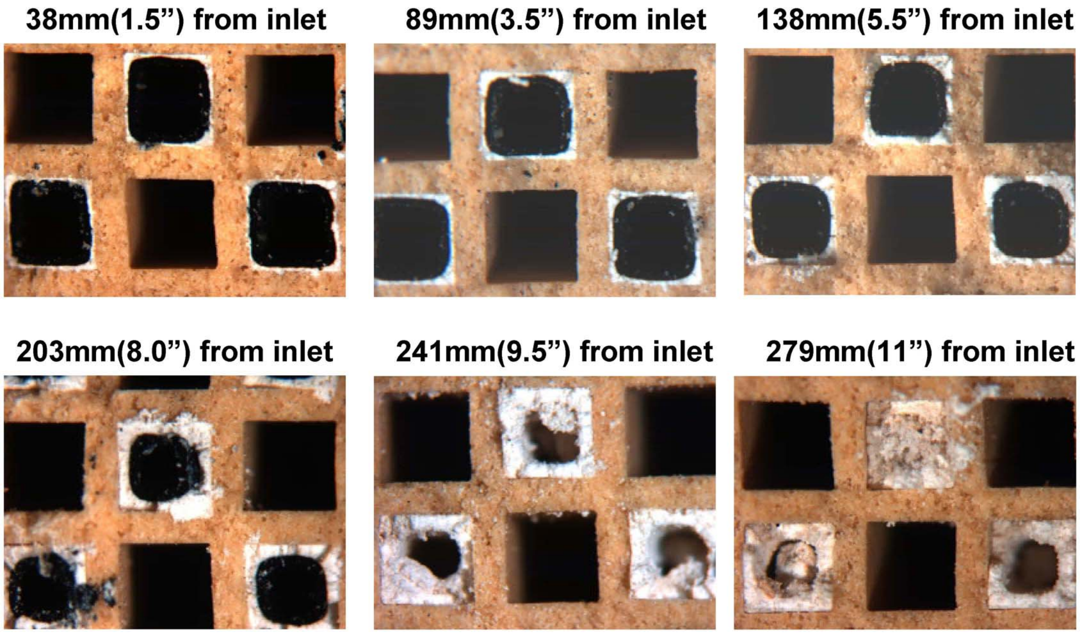


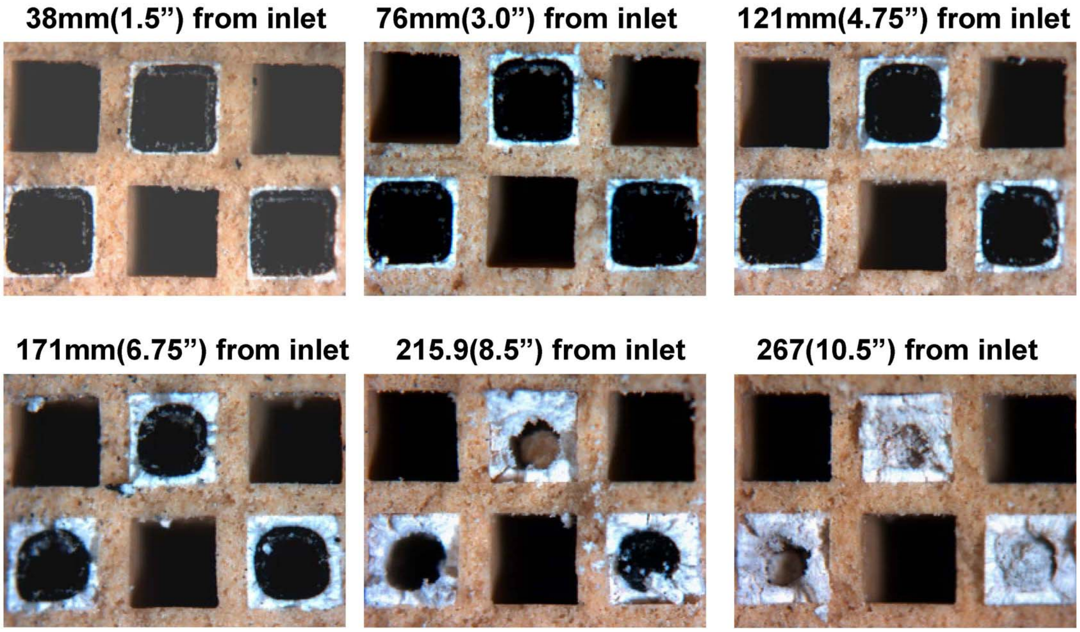
**Figure 22. Ash composition variation along filter length**

Figures 23, 24, 25 illustrate the variation of ash distribution at radial center, mid-radius and near skin along the length of the filter.



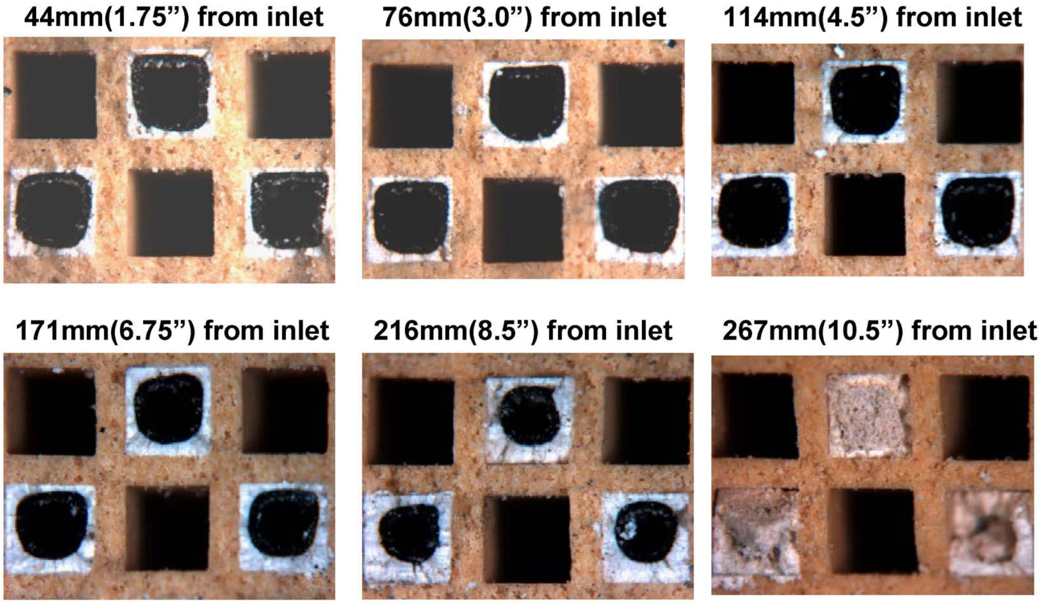
38mm(1.5”) from inlet
89mm(3.5”) from inlet
138mm(5.5”) from inlet
203mm(8.0”) from inlet
241mm(9.5”) from inlet
279mm(11”) from inlet

Figure 23. Ash distribution (radial view) along filter length at Radial Center



38mm(1.5”) from inlet
76mm(3.0”) from inlet
121mm(4.75”) from inlet
171mm(6.75”) from inlet
215.9(8.5”) from inlet
267(10.5”) from inlet

Figure 24. Ash distribution (radial view) along filter length at Mid-Radius



44mm(1.75”) from inlet

76mm(3.0”) from inlet

114mm(4.5”) from inlet

171mm(6.75”) from inlet

216mm(8.5”) from inlet

267mm(10.5”) from inlet

**Figure 25. Ash distribution (radial view) along filter length at skin**

## SUMMARY & CONCLUSIONS

The impact of ash accumulation on pressure drop for Robust Cordierite (RC) 200/19 and Robust Cordierite (RC) ACT 270/16 was evaluated. A test methodology with periodic ash accumulation with a custom developed accumulation cycle and filter Δp characterization was applied. The ash accumulation was accelerated by using a high load profile ash accumulation cycle and by low filter volume to engine-power-output ratio. The lubricating oil consumption was tracked by a drain-and-weigh method. The highest lube oil consumption was found to be at high speed-high load operation; hence the ash accumulation cycle had a high load profile. The ash accumulation was determined by weight gain of the filter after soot burnout. The ash finding rate in the DPF based on 1.69 wt% ash content lube oil was 55-60% which is slightly lower than expected. The low ash finding rate was mostly attributed to the disproportional evaporation of low ash content oil components.

At initial condition (without ash) the Robust Cordierite (RC) ACT filter exhibited lower pressure drop at high soot loads. The Robust Cordierite (RC) ACT exhibited higher pressured drop in the clean state. The soot loaded pressure drop with ash exhibited three major phases. Initially with small ash conditioning pressure drop decreased due to the transition from deep penetration to cake filtration of soot (conditioning). This was followed by a moderate linear increase in soot loaded pressure drop, due to reduction in effective filter volume with increasing ash levels. In the final phase the soot loaded pressure drop increased significantly with small increments in ash, due to inlet channel throttling effect due the large amount of ash along with soot. The pressure drop limit of 25kPa (1250m³/hr & 200°C at 6g/l soot load) was reached by Robust Cordierite (RC) standard and Robust Cordierite (RC) ACT filters at 680g (40g/l) and 929g (55g/l) ash respectively.

The ash accumulation in the filter was a combination of ash deposition on the inlet walls and as an ash-plug at the outlet end of the inlet channels. This was attributed to the ash accumulation cycle having low load and high load modes of operation, as well as active regenerations.

The 200/19 filter and ACT 270/16 filter logged over 1700 engine hours (300k miles regeneration equivalent) and over 2600 engine hours (450k miles regeneration equivalent) over the entire testing. The filters exhibited good filtration efficiency throughout the testing. Steady state ramped model cycle emission tests were performed at the end of test. The PM emissions were 7% of the 2007 PM emission limits. The filters also exhibited excellent filtration efficiency (>99.5%). Both the filters did not show any physical degradation after testing supporting the excellent thermal durability of Robust Cordierite (RC) material for diesel particulate filters.

The Robust Cordierite (RC) ACT 270/16 exhibited 30% ash storage advantage than Robust Cordierite (RC) 200/19.The higher ash capacity of the ACT design may be utilized for

- Lowering life time pressure drop with soot and/or ash
- Extending ash cleaning intervals
- Reducing filter volume for a given pressure drop limit
- Or a combination of the above

based on specific application constraints.

## ACKNOWLEDGMENTS

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