

Ash Effects on Diesel Particulate Filter Pressure Drop Sensitivity to Soot and Implications for Regeneration Frequency and DPF Control

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Massachusetts Institute of Technology

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ABSTRACT

Ash, primarily derived from diesel engine lubricants, accumulates in diesel particulate filters directly affecting the filter's pressure drop sensitivity to soot accumulation, thus impacting regeneration frequency and fuel economy. After approximately 33,000 miles of equivalent on-road aging, ash comprises more than half of the material accumulated in a typical cordierite filter. Ash accumulation reduces the effective filtration area, resulting in higher local soot loads toward the front of the filter. At a typical ash cleaning interval of 150,000 miles, ash more than doubles the filter's pressure drop sensitivity to soot, in addition to raising the pressure drop level itself.

In order to evaluate the effects of lubricant-derived ash on DPF pressure drop performance, a novel accelerated ash loading system was employed to generate the ash and load the DPFs under carefully-controlled exhaust conditions. The ash loading system utilized a conventional CJ-4 oil and was coupled to the exhaust of a Cummins ISB diesel engine, allowing for accelerated ash loading and DPF performance evaluation with realistic exhaust conditions. Following DPF performance evaluation, the filters were subjected to a detailed post-mortem analysis in which key ash properties were measured and quantified.

Measurements of ash properties and distribution provide key information to interpret the experimental results. In parallel with the experiments, theoretical models were developed and utilized to provide additional details regarding the underlying mechanisms responsible for the manner in which ash alters DPF channel geometry and affects the conditions under which soot is accumulated. The results show a significant increase in local soot loads, elevated filter wall velocities, and

a resulting increase in the Peclet number with ash accumulation. Based on the DPF post-mortem analysis and theoretical models, explanations for the differences in DPF pressure drop sensitivity to soot for ash-loaded filters and DPFs containing no ash were developed.

INTRODUCTION

Diesel particulate filters (DPF) have been in widespread use to meet increasingly stringent particulate matter (PM) emissions regulations since 2007. These filters function by trapping soot on the filter surface and within the porous walls, with trapping efficiencies in excess of 99%, in some cases. Over time, soot accumulation in the DPF increases exhaust backpressure, requiring periodic cleaning (regeneration), whereby the soot is oxidized leaving a small amount of inorganic ash behind. Prior to the widespread introduction of DPFs on a large scale, the majority of research efforts were devoted to understanding the soot accumulation and filtration processes, filtration efficiencies, and DPF regeneration. While extremely important for the practical application and successful operation of diesel particulate filters, these processes all occur over a relatively short time scale, of the order of several hours. As a result of these significant research efforts, soot deposition processes, soot effects on DPF pressure drop characteristics, and filter regeneration are fairly well understood.

On the other hand, inorganic ash accumulates relatively slowly following successive regeneration events and impacts DPF performance over much longer time scales, typically of the order of several thousand hours. The long run time required for a significant amount of ash to accumulate in the DPF is primarily due to the small amount of ash in the particulate matter, generally in the range of 0.5% to 1.0% [1]. Further, the small contribution of ash to the total engine-out

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PM emissions is a direct function of the ash sources, the majority of which originates in lubricant additives [2,3,4]. Due to these extremely long time scales, much less is known about the impact of ash accumulation on DPF performance over the filter's useful life.

The significance of the ash issue is perhaps best illustrated by Figure 1, which shows the ash fraction of the accumulated material in the DPF (ash and soot) over the total mileage before ash cleaning. These estimates are based on a DPF volume roughly twice the engine swept volume, which is typical of production systems. After only slightly more than 33,000 miles, nearly half of the material trapped in the DPF is ash, considering a maximum DPF soot load of 6 g/l prior to regeneration. Furthermore, prior to the EPA's minimum mandated DPF service interval of 150,000 miles, more than 80% of the material accumulated in the DPF is ash, with soot making up less than 20%.

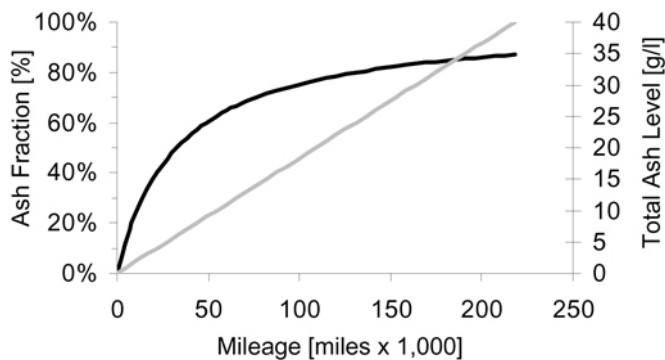


Figure 1. Ash fraction of the total accumulated material in the DPF as a function of total mileage prior to ash cleaning assuming a maximum DPF soot load of 6 g/l for regeneration.

Previous studies of ash accumulation in diesel particulate filters show ash forming a layer along the channel walls, and generally also accumulating in end-plugs toward the back of the DPF channels [5,6,7]. Furthermore, due to the significant amount of ash accumulated in the DPF, it is rare, with the exception of the first several thousand miles, for the DPF to behave as a “clean” filter. Nonetheless, most of the DPF research over the last twenty years has focused almost exclusively on understanding the behavior of “clean” filters containing no ash and only soot.

SOOT PROPERTIES AND THEIR EFFECT ON DPF PERFORMANCE

The emphasis on understanding the soot accumulation processes and soot properties within the DPF has yielded a significant knowledge base and well-developed theoretical understanding of the fundamental processes and parameters controlling soot properties and DPF pressure drop. Much of these fundamental theories can be extended to describe ash

effects and ash/soot interaction as well, and it is therefore instructive to briefly review the current theoretical framework.

The total pressure drop through the DPF is the sum of a number of factors and is influenced by the filter geometry, substrate properties, and the properties of the accumulated material (ash and soot). While extensive DPF pressure drop models have been developed and described elsewhere [8,9,10], the aim of the present discussion is simply to highlight key parameters useful to understanding the ash impact. Mathematically, the total DPF pressure drop can be described as follows:

$$\Delta P_{Total} = \Delta P_{In} + \Delta P_{Out} + \Delta P_{Channel} + \Delta P_{Wall} + \Delta P_{Ash} + \Delta P_{Soot} \quad (1)$$

where $\Delta P_{In/Out}$ is the pressure drop associated with the contraction and expansion of the exhaust gases at the filter inlet and outlet, $\Delta P_{Channel}$ is the pressure drop due to frictional losses for gas flow along the length of the channel, and $\Delta P_{Wall/Ash/Soot}$ are the pressure losses associated with flow through the porous media including the filter wall, soot layer, and ash layer.

In most cases, the pressure losses associated with flow through the porous filter walls, and soot and ash layers, provide the largest contribution to filter pressure drop. The flow through a porous media can be described using Darcy's Law. In most practical applications of diesel particulate filters the Reynolds number for flows through the porous layers is much less than one, and inertial terms can be neglected as a first-order approximation, giving the following relationship:

$$\Delta P_{Wall/Ash/Soot} = \left(\frac{\mu}{K_p} \right) \cdot v_w \cdot w \quad (2)$$

where μ is the exhaust gas dynamic viscosity, K_p is the permeability of the porous media, v_w is the gas wall velocity, and w is the layer thickness. Ash and soot accumulation in the DPF increases the material layer thickness, w , and introduces additional flow resistance through the porous layer, reflected in the layer permeability, K_p [11].

While the application of the simple DPF pressure drop model described above is fairly straightforward, complications arise in accurately defining the material properties, specifically the permeability and thickness of the porous media. The significant research efforts studying soot accumulation in the DPF have yielded a well-developed understanding of soot properties and their variation with particle size, and exhaust

conditions, however relatively little is known about the parameters controlling ash properties.

Studies by Konstandopoulos et al. have shown soot properties to be well correlated to the Peclet number (Pe), which provides a measure of inertial and diffusional deposition [12]. The Pe number can be computed as follows:

$$Pe = \frac{U_w \cdot d_{Primary}}{D} \quad (3)$$

where U_w is the filtration velocity, $d_{Primary}$ is the primary soot particle diameter (typically $\sim 25\text{-}40$ nm), and D is the diffusion coefficient, which depends on the exhaust gas conditions and soot agglomerate particle size. A high value for the Pe number results in more inertial deposition and a more densely packed soot layer, whereas a low value for the Pe number results in a more loosely packed soot layer due primarily to diffusional deposition. A detailed discussion of the parameters affecting the Peclet number and its calculation can be found in [12]. Figures 2 and 3 present the variation in soot properties as a function of the Pe number.

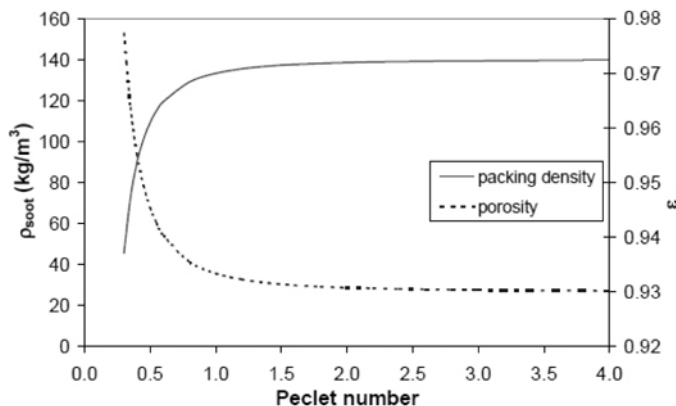


Figure 2. Soot packing density (ρ_{soot}) and porosity (ϵ) as a function of the Peclet number. Adapted from [13]. Reprinted with permission from SAE paper 2004-01-1133 © 2004 SAE International.

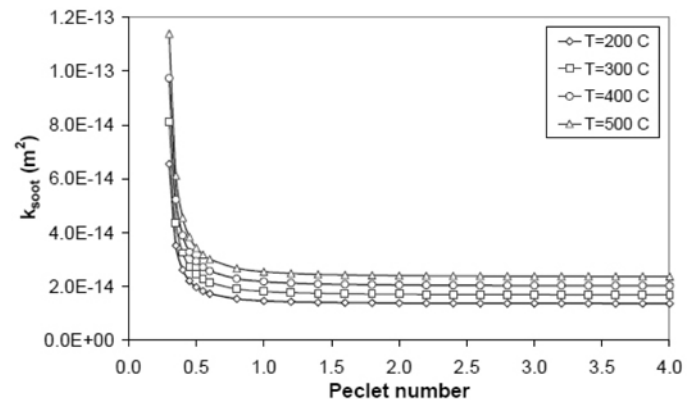


Figure 3. Soot permeability (k_{soot}) as a function of the Peclet number. Adapted from [13]. Reprinted with permission from SAE paper 2004-01-1133 © 2004 SAE International.

As evident in Figures 2 and 3, the soot properties of interest are extremely sensitive to small variations in the Peclet number, particularly for $Pe < 1$. Besides the correlations presented above, still other investigations have shown some dependence of soot properties on the amount of soot deposited in the DPF, in addition to the soot particle size and filtration velocities. Figure 4 presents the variation in measured soot packing density as a function of DPF wall velocity and total soot load. The experimental data presented in Figure 4 was based on measured soot layer properties for soot accumulated in a single channel DPF sample under carefully-controlled conditions. The authors further estimated soot layer permeability based on the experimental data, and additional details can be found in [14].

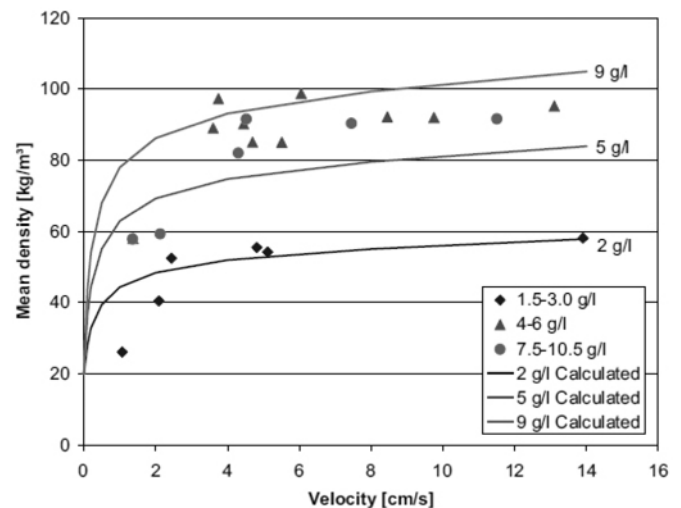


Figure 4. Soot layer packing density as a function of filtration velocity and DPF soot load, from [14]. Reprinted with permission from SAE paper 2006-01-0261 © 2006 SAE International.

Based on the data available in the literature and summarized above, the variation of soot properties with exhaust conditions and soot particle size is fairly well understood. The parameters controlling ash formation and accumulation within the DPF are not nearly as well-known as those controlling PM deposition, much less the resulting ash layer properties. This study aims to investigate the manner in which ash accumulation affects soot distribution and the properties of the accumulated soot in the DPF, and addresses practical implications for DPF operation and regeneration control.

ASH EFFECTS ON DPF PRESSURE DROP PERFORMANCE

Previous studies investigating ash effects on DPF performance have identified a number of key issues warranting further investigation. Recent work has shown that engine-out ash is transported to the DPF intimately bound to the carbonaceous soot. These observations imply the ash in the exhaust stream to be of the same size or smaller than the carbonaceous soot agglomerates, typically on the order of 100 nm [1]. Further, following repeated regenerations, ash particle size, as measured in the DPF, is typically reported between 1 μm and 5 μm , indicating some degree of ash agglomeration/sintering following deposition in the DPF [15,16,17,18]. Unlike the soot cake properties, which have been shown to be primarily influenced by the soot particle deposition mechanisms (Figures 2,3,4); the properties of the accumulated ash are a strong function of the conditions and temperature history within the DPF over repeated regeneration cycles.

The effect of DPF temperature history on ash packing density was clearly shown in a recent study reporting an increase in ash packing density by up to 60% when the ash was heated from 750 $^{\circ}\text{C}$ to 1100 $^{\circ}\text{C}$. Internal DPF temperatures within this range are often experienced for short periods of time during active DPF regeneration. The same study also showed elevated temperatures affecting ash composition, with the increased formation of metal oxides and some ash decomposition observed at temperatures above 850 $^{\circ}\text{C}$ [18].

In addition to influencing ash properties, exhaust temperature and flow conditions, as well as regeneration strategy have also been shown to affect ash distribution within the DPF. In general, filters regenerated periodically tend to show a significant amount of ash accumulated in the channel end-plugs, with less ash deposited along the channel walls. On the other hand, filters regenerated continuously result in the ash preferentially accumulated along the channel walls, with little end-plug formation [18, 19].

As indicated in Figure 1, a substantial amount of ash (relative to soot) builds up in the DPF fairly rapidly. Measurements of ash deposited along the DPF channel walls have reported

thicknesses in the range of 0.05 mm to 0.15 mm for DPFs regenerated periodically [6,7, 20]. At these ash levels, in the range of 20 g/l to 40 g/l, the soot is deposited directly on top of the ash layer. In fact, the soot may never even come in contact with the substrate, and the DPF effectively functions as an “ash holder” with the ash actually filtering the soot. In some cases, particularly for relatively low ash loads, the ash forms a membrane preventing soot accumulation in the DPF pores, and actually provides a pressure drop benefit by eliminating the rapid pressure rise typically associated with soot depth filtration [17, 18].

At elevated ash levels, above 15 g/l, the effect of the ash on DPF pressure drop performance is primarily detrimental. Not only does the ash increase the total filter pressure drop, but it also increases the filter's pressure drop sensitivity to soot accumulation [6, 18]. It has been proposed that the primary factor responsible for the observed increase in pressure drop sensitivity is predominantly a geometric effect, that is the ash occupies a significant fraction of the DPF volume, displacing the soot and resulting in elevated local soot levels toward the front of the filter [6]. Further, in occupying a considerable amount of the DPF, the ash also drives up the filter wall velocities which can have a substantial effect on the properties of the soot deposits as indicated in Figures 2,3,4.

While the authors have previously reported on these observations, this work aims to provide additional details through careful analysis of the experimental data and application of the prevalent filtration theory. Further, of practical importance are the implications of these results for DPF regeneration frequency and filter control, which is primarily based upon pressure drop measurements combined with predictive models. The results show that ash does, in fact, have a significant effect on DPF pressure drop behavior, and that these effects must be accounted for to accurately determine DPF soot load and optimize DPF regeneration over the filter's useful service life.

EXPERIMENTAL SET-UP AND PROCEDURES

The experiments described in this study were conducted under carefully-controlled conditions utilizing commercial (fully-formulated) lubricants. The DPFs were loaded with ash using a specially designed accelerated ash loading system, and DPF performance evaluation followed a set procedure using the Cummins ISB and a separate flow bench. The detailed experimental set-up and procedures follow those described previously in [6, 18, 21].

ENGINE AND INSTRUMENTATION

The engine used in this study was a pre-production Cummins development engine based on the ISB 300 engine platform. The ISB 300 is a 6 cylinder, 5.9 liter, turbocharged, direct

injection diesel engine. The engine is rated at 224 kW (300 hp) at 2500 rpm and 890 N-m (660 ft-lb) at 1600 rpm. The ISB 300 is equipped with a high-pressure common rail fuel injection system, variable geometry turbocharger, and cooled exhaust gas recirculation (EGR). [Table 1](#) provides additional details regarding the engine specifications and geometry.

Table 1. Cummins ISB 300 engine specifications.

Engine Parameter	Description
Model	ISB 300
Maximum Torque	890 N-m @ 1600 rpm
Maximum Power	224 kW @ 2500 rpm
Cylinders	in-line 6
Displaced Volume	5.9 liters
Combsution System	direct injection, 4-stroke
Injection System	common rail
Aspiration	variable geometry turbocharger and intercooler

ASH LOADING SYSTEM

The accelerated ash loading and aftertreatment aging system was designed to load a conventional D5.66" (14.38 cm) × 6" (15.24 cm) DPF to 40 g/l of ash in slightly under 100 hours. A simplified schematic of the test system is shown in [Figure 5](#), and additional details are presented in [Figure A-1](#) in the [Appendix](#). The accelerated ash loading system is coupled to the exhaust of the Cummins ISB, enabling the feed-gas particulate and ash characteristics to be carefully controlled and monitored.

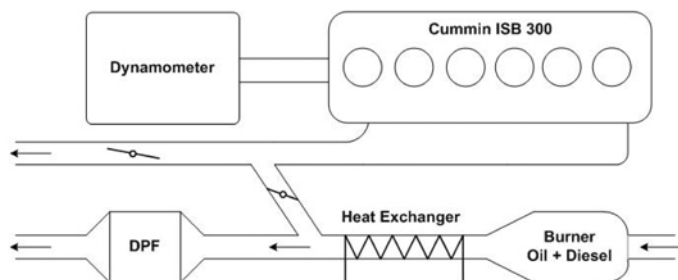


Figure 5. Experimental set-up showing accelerated ash loading system mounted beside Cummins ISB test bed.

The accelerated ash loading system, described above, has been validated in previous studies. Work by the authors reported in 2008 showed a detailed comparison between engine-out ash and PM characteristics from the Cummins with the characteristics of the ash and particulate matter produced using the accelerated loading system. No significant differences other than increased exhaust ash levels with the accelerated ash loading system were noted [21]. More recent work presented a comparison of DPFs aged in the laboratory using the accelerated ash loading system and simulating 180,000 miles of on-road use, with filters subjected to 180,000 miles of on-road fleet testing using CJ-4 oils. Ash

properties, composition, and distribution were very similar for both the laboratory and field-aged filters [18].

The accelerated ash loading system is composed of a diesel burner and custom combustion chamber. A secondary air-assisted oil injector allows for precise control of lubricant introduction into the combustor. [Table 2](#) presents the system's operating specifications and [Figure A-1](#) in the [Appendix](#) depicts the system lay-out. A heat exchanger mounted downstream of the combustor provides additional control over exhaust temperature, independent of the burner settings, allowing for online DPF regeneration. In this manner DPF inlet temperatures can easily be controlled between 200 °C and 800 °C.

Table 2. Accelerated ash loading system specifications.

System Parameter	Description
Fuel Consumption	1.5 - 7.6 l/h
Oil Consumption	0.94 - 9.4 ml/min
Injection Pressure	700 - 1400 kPa
Air Flow	266 - 1130 slpm
DPF Inlet Temperature	200 - 800 °C

A junction after the heat exchanger outlet connects the Cummins exhaust system to the accelerated ash loading rig. A portion of the ISB's exhaust can be routed to the ash loading system, providing a realistic exhaust composition (gaseous and PM). With the burner switched off, the test set-up also functions as a flow bench. Additional details regarding system design and performance can be found in [6, 18].

TEST MATRIX AND PROCEDURES

An SAE 15W-40 commercially available CJ-4 diesel engine oil was used in this study to accurately simulate ash generated by lubricants currently used with DPF-equipped engines. The CJ-4 oil has a sulfated ash content of approximately 1.0%. The elemental composition of the lubricant is listed in [Table 3](#).

Table 3. Lubricant elemental composition. *Value supplied by manufacturer.

Lubricant	ASTM D5185							
	B [ppm]	Ca [ppm]	Fe [ppm]	Mg [ppm]	P [ppm]	Zn [ppm]	S [ppm]	Mo [ppm]
CJ-4	586	1388	2	355	985	1226	3200*	77

Both the Cummins ISB and the diesel burner on the accelerated ash loading system were fueled with an ultra-low sulfur diesel (ULSD, 15 ppm S) fuel. In order to rule out metals in the fuels contributing to the DPF ash, the test fuels were periodically analyzed to monitor the trace metals

content. All trace elements in the diesel fuel were below the minimum detectable limits of the analysis (ASTM D5185).

The cordierite diesel particulate filters used in this study measured D5.66" (14.38 cm) × 6" (15.24 cm) giving a total DPF volume of 2.47 liters with a cell geometry of 200 cells per in² (31 cells per cm²) and a wall thickness of 0.012 in (0.30 mm). All of the filters were coated with a platinum catalyst and washcoat. Aside from instrumentation with several thermocouples, the locations of which are shown in [Figure A-1](#) of the [Appendix](#), the DPFs were not altered in any way.

The test procedure was designed to allow for careful control and monitoring of ash composition and exhaust conditions. All DPF performance evaluation was conducted using either the Cummins ISB or the flow bench. The accelerated ash loading system was only used to load the particulate filters with ash. The combined effects of soot and ash on DPF pressure drop were also studied. In this case, the filters were loaded to a predetermined ash level using the accelerated ash loading system, and subsequent soot loading was accomplished using only the Cummins ISB. Due to the small filter volume, only a portion of the exhaust from the engine was diverted to flow through the DPF when the engine was used.

Initially all of the DPFs were subjected to a degreening cycle using the burner with no oil injection to expose the filters to a series of high temperature cycles. Supplementary exhaust from the Cummins ISB was also used to load the filter with soot. Following complete DPF regeneration, the filter was weighed hot to determine its clean weight. The balance used to weigh the DPF has a 12 kg maximum capacity with 0.2 g resolution. All DPF ash and soot loading reported in this paper was determined by weighing the DPF hot to eliminate error due to condensed water in the filter. DPF internal temperatures at the time of weighing were around 200 °C.

The specifics of the ash loading procedure used in this study were previously described in detail [6, 18]. All of the DPFs were subjected to periodic regeneration. Typical soot loading conditions were at a filter inlet temperature of 250 °C for one hour followed by filter regeneration at an inlet temperature of 620 °C for 15 minutes. The loading and regeneration cycles were repeated over the course of the ash loading protocol.

The maximum specific DPF ash load achieved in this study was 42 g/l. This level of ash accumulation is estimated to be equivalent to roughly 240,000 miles (386,000 km) or 5,960 hours of DPF operation. This estimate is based on the following assumptions for a typical medium heavy-duty diesel engine: 15 g/hr average oil consumption [22], 40 mi/hr (64 km/hr) average speed, and a full sized particulate filter volume of 12 liters.

Unless otherwise noted, all of the pressure-drop data presented in this paper was acquired from the flow bench measurements using air at ambient conditions. Use of the flow bench provides more repeatable flow conditions for each test. Following ash loading and performance evaluation, all of the filters were subjected to a detailed post-mortem analysis.

FILTER POST-MORTEM ANALYSIS

For the post-mortem analysis, each DPF was axially sectioned into two equal and symmetric halves. One of the filter half sections was further divided into four 1.5 inch (3.8 cm) long sections axially. The axial sections were subdivided into five samples corresponding to different radial positions. Each DPF sample consisted of approximately 140 to 180 individual cells. In this manner, twenty core samples were obtained from each filter, allowing for measurement of ash distribution and of ash properties' variation in both the axial and radial directions in the DPF. Details of the procedures utilized for filter post-mortem analysis were described in [6]. All ash properties were measured directly in the DPF, with great efforts to minimize disturbances to the ash during sample preparation.

EXPERIMENTAL RESULTS

Initial studies to characterize baseline DPF performance with and without ash are shown in [Figure 6](#). The figure shows pressure drop as a function of soot load for a DPF containing 42 g/l ash and a filter containing no ash. It is estimated that 42 g/l ash corresponds to approximately 240,000 miles or 5,960 hours of equivalent on-road DPF aging, based on the assumptions described in the previous section.

While the pressure drop response for the DPF containing only soot and no ash exhibits the characteristic depth and cake filtration regimes, the behavior of the DPF containing ash and soot is quite different. For the DPF containing no ash, soot is initially trapped in the filter pores (depth filtration) which gives the characteristic rapid rise in pressure drop shown in [Figure 6](#). As the DPF continues to accumulate soot, building a filter cake, pressure drop increases less rapidly and in a linear fashion. On the other hand, the accumulated ash layer forms a physical barrier preventing soot from reaching the filter pores. However, as the soot cake builds on the ash layer, the increase in filter pressure drop is clearly non-linear. These results were previously reported in [6], however this work aims to explore the underlying factors responsible for the observed results in detail.