SLOAN AUTOMOTIVE LABORATORY

A Consortium to Optimize Lubricant and Diesel Engines for Robust Emission Aftertreatment Systems

Characteristics and Effects of Lubricant Additive Chemistry and Exhaust Conditions on Diesel Particulate Filter Service Life and Vehicle Fuel Economy

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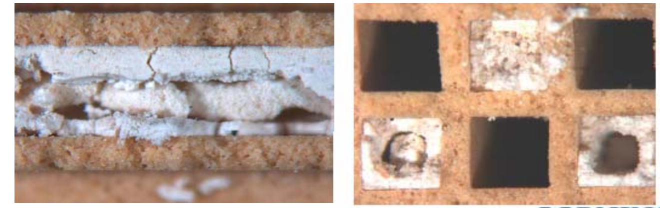
DEER 2009 DEARBORN
DIRECTIONS IN ENGINE-EFFICIENCY AND EMISSIONS RESEARCH CONFERENCE
U.S. DEPARTMENT OF ENERGY

Ash Impacts Diesel Particulate Filter Performance

Courtesy: E. Senzer



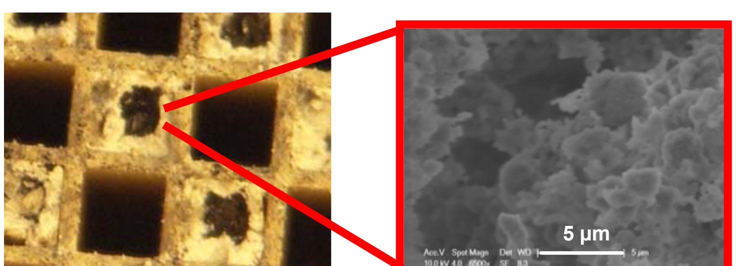
Source: K. Aravelli

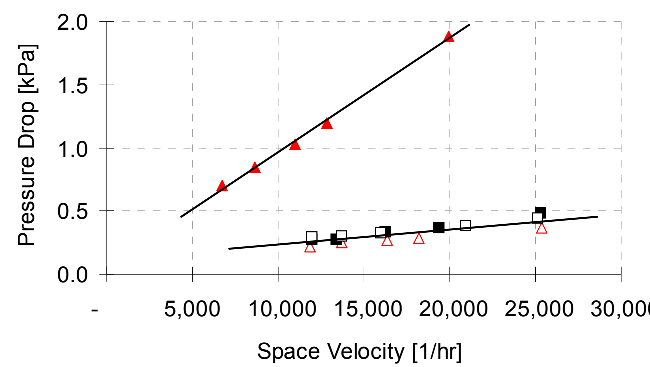
CORNING

- **Ash Sources**
  - **Lubricant additives (Zn, Ca, Mg, S, P)**
  - Engine wear, corrosion, trace metals in fuels

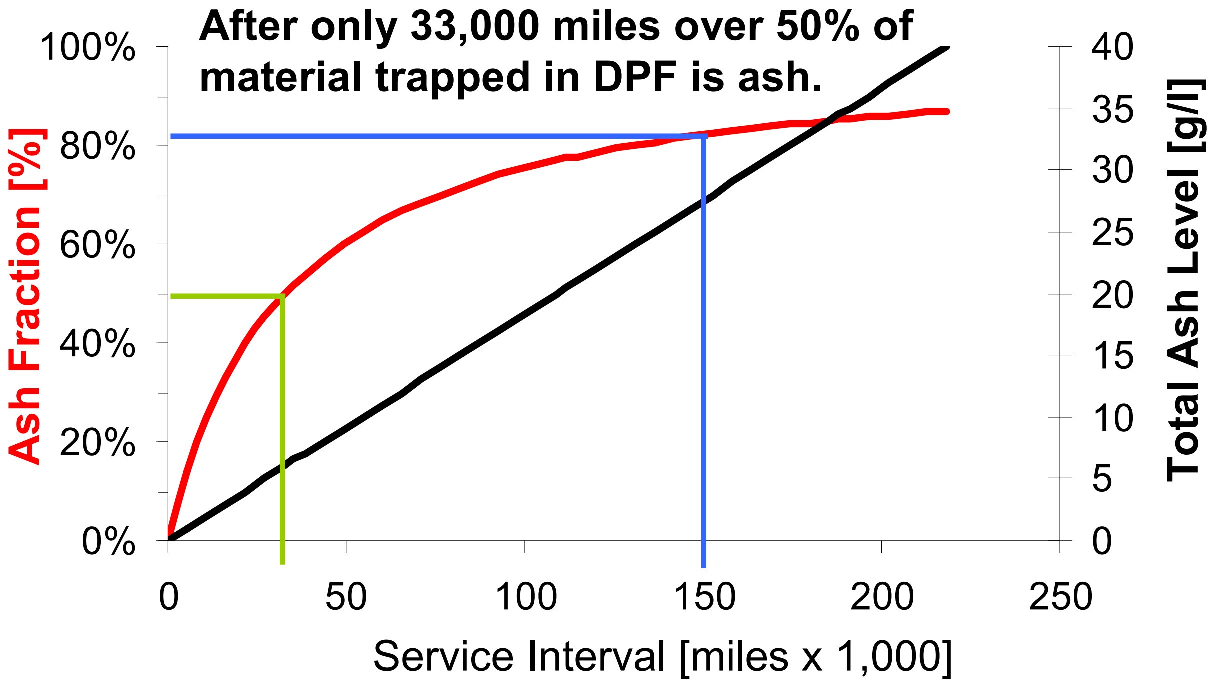
- **Ash Mitigation**
  - CJ-4 oil specification - limits sulfated ash to 1.0% maximum
  - Novel DPF designs and substrates – asymmetric, membranes, and others
  - Reduced engine oil consumption

Fundamental Understanding of Ash Properties Lacking



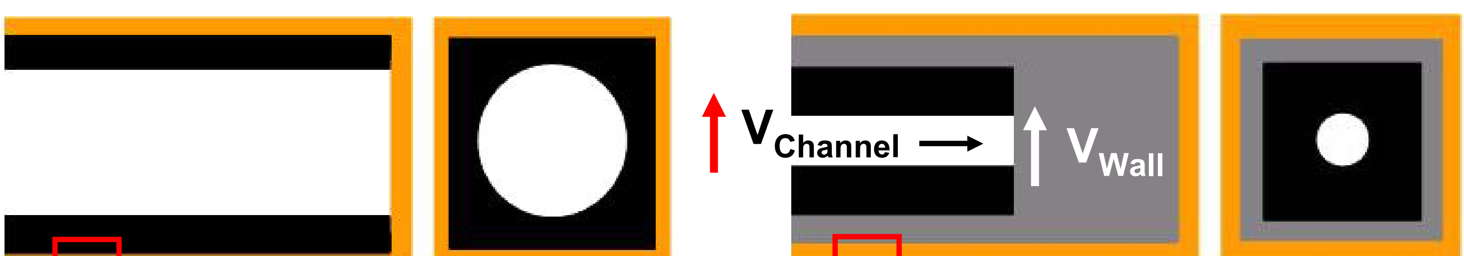


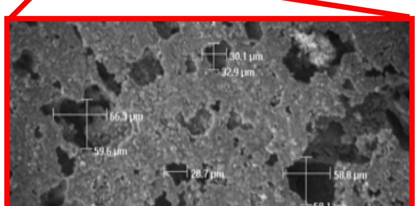
Most of Material Trapped in DPF is Ash



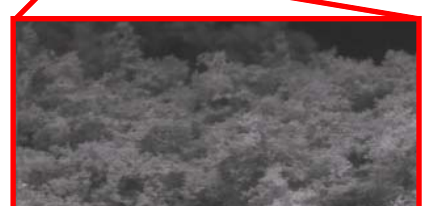
Ash @ 42 g/l:

- 75% ash in end-plug (vol.)
- -27% DPF channel area
- -40% DPF channel length





No Ash



Ash

Experimental Apparatus – DPF Performance Testing

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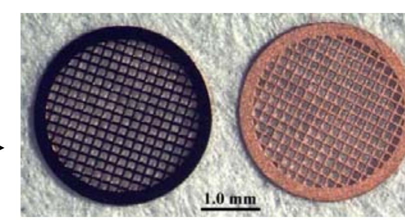
Cummins ISB used for DPF performance evaluation before and after ash loading tests on accelerated test rig.

- **Cummins ISB 300**
  - Variable geometry turbocharger
  - Cooled EGR
  - Common rail fuel injection
  - Fully electronically controlled
- **Gaseous Emissions**
  - CAI 300 HFID – Hydrocarbons
  - CAI 400 HCLD – NO/NOx
  - CAI 602P NDIR – CO/CO2/O_2
  - API 100 E – SO_2
- **Particulate Emissions**
  - Sampling and comparison to burner

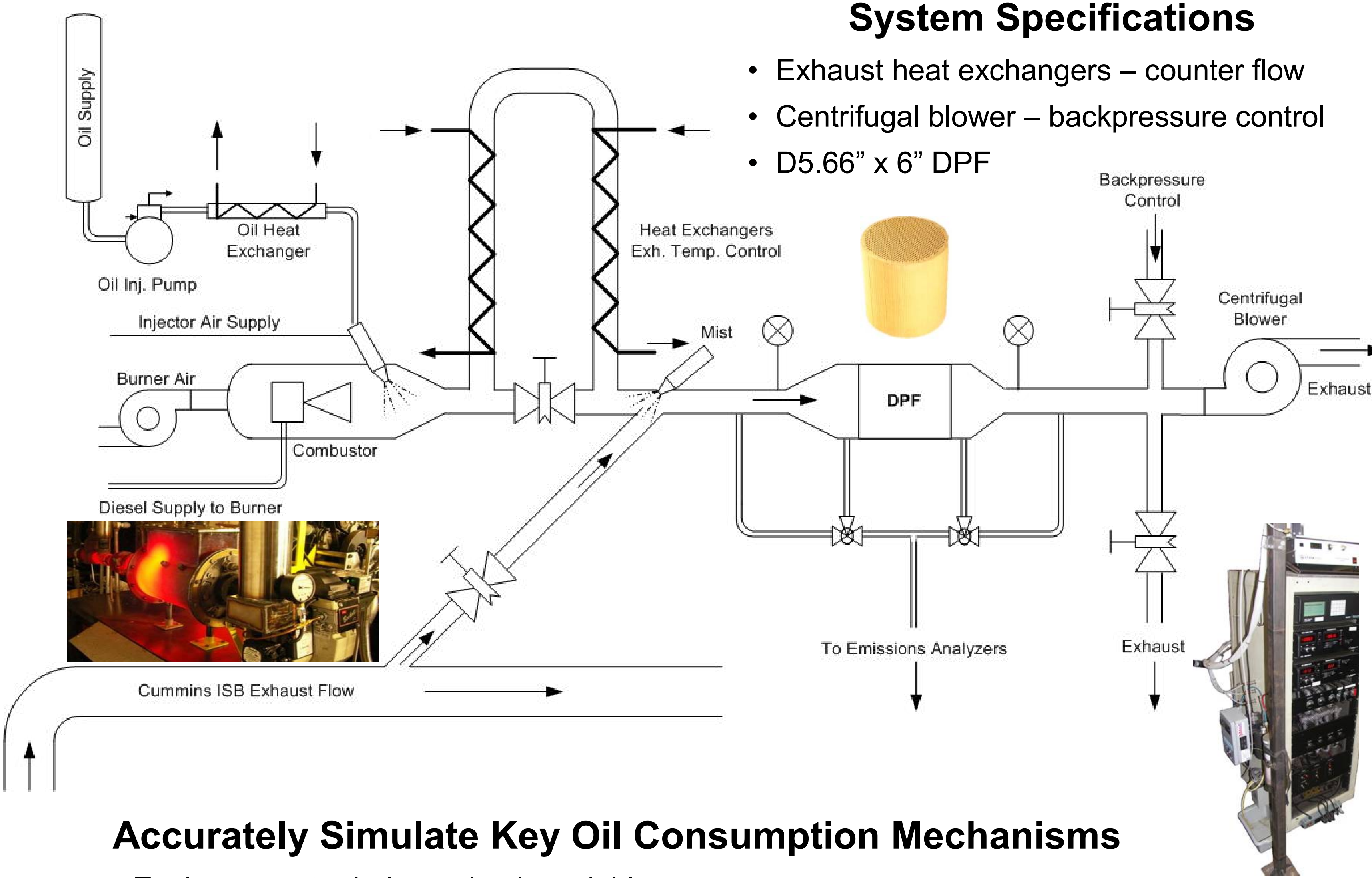
Cummins ISB 300 with DPF



Accelerated Ash Loading System

System Specifications

- Exhaust heat exchangers – counter flow
- Centrifugal blower – backpressure control
- D5.66" x 6" DPF



Accurately Simulate Key Oil Consumption Mechanisms

- Each parameter independently variable
- Precise control of quantity and characteristics of ash generated

Key Test Parameters

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DPF Specifications

- Substrate – Cordierite D5.66” x 6” 200/12, catalyzed

Lubricant Composition

- All oils except pure base oil formulated to 1% sulfated ash

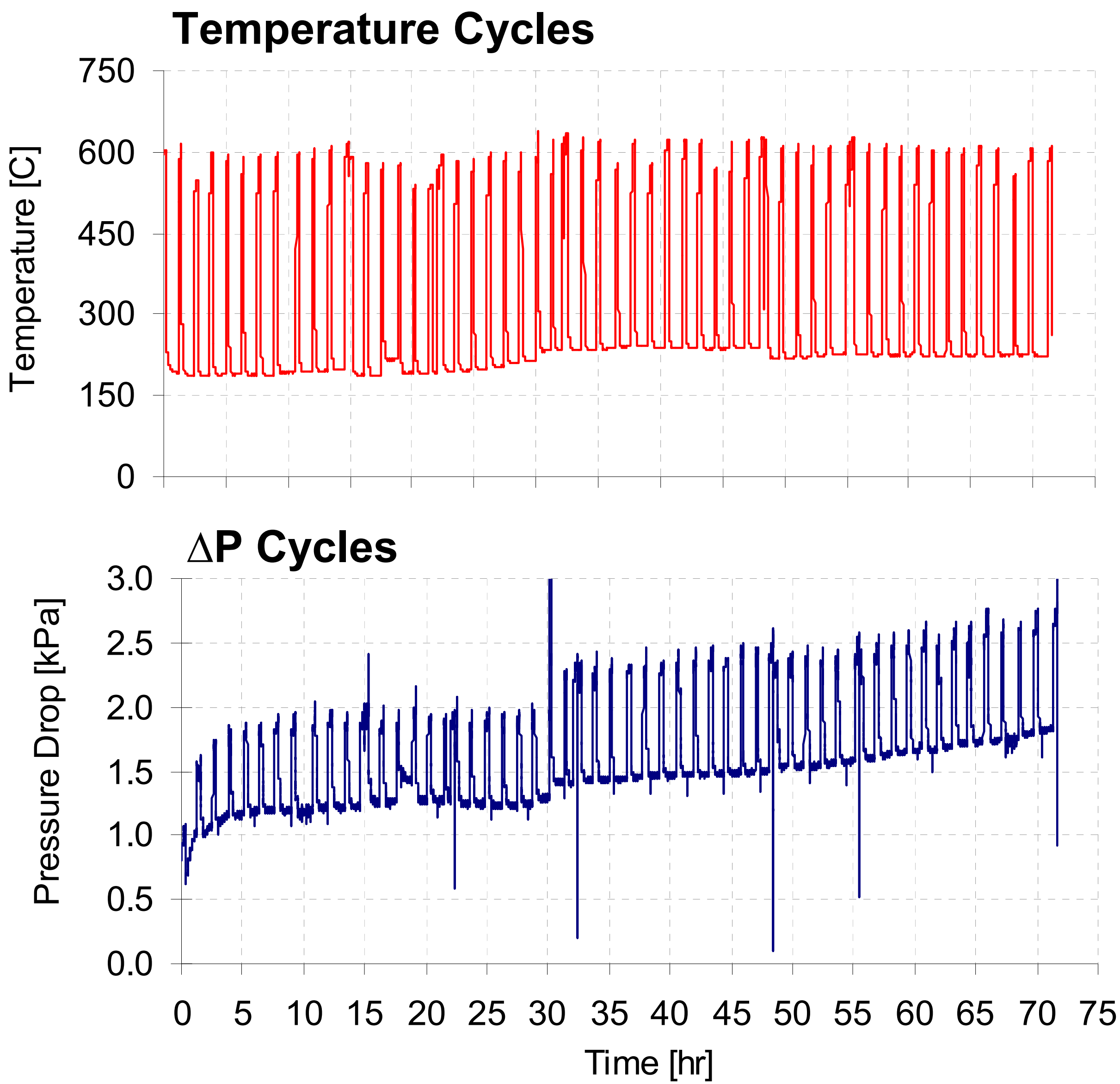
	ASTM D5185							
Lubricant	B [ppm]	Ca [ppm]	Fe [ppm]	Mg [ppm]	P [ppm]	Zn [ppm]	S [ppm]	Mo [ppm]
CJ-4	586	1388	2	355	985	1226	3200*	77
Base Oil	1	<1	<1	<1	8	<1	60	<1
Base Oil + Ca	3	2928	1	5	2	<1	609	<1
Base Oil + ZDDP	1	<1	<1	<1	2530	2612	6901	<1

Test Fuel - ULSD (Metals below ICP MDL ~1.0 – 0.05 ppm)

DPF Ash Loading

- Ash loading to max 42 g/l (equivalent on-road exposure ~ 240k miles)
- Periodic regeneration cycle

Typical Accelerated Ash Loading Cycle

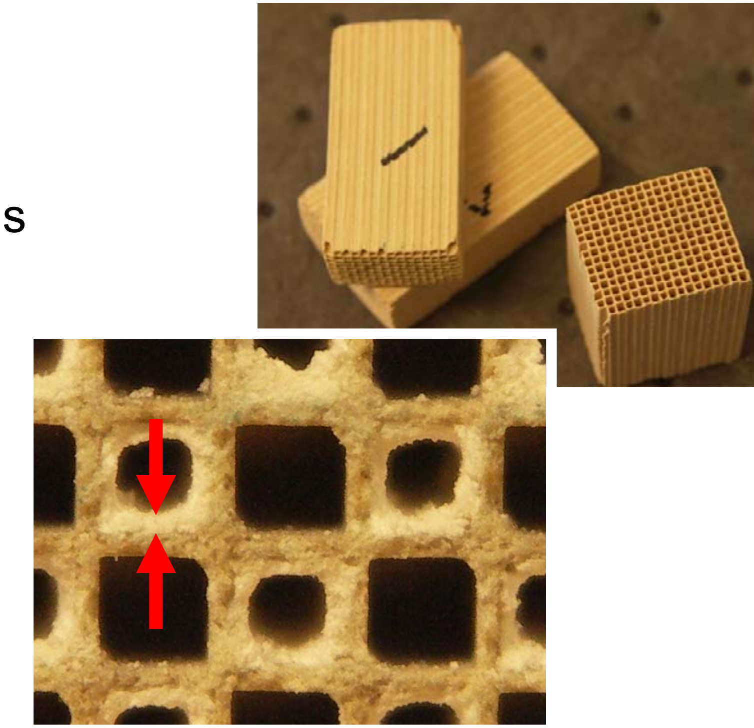


Loading Cycle

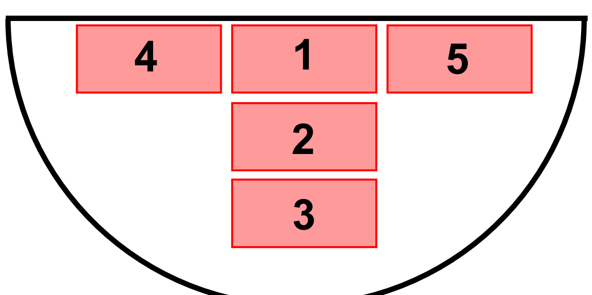
- 55 cycles
- 1 hour loading @ 250 °C inlet
- 15 min. regen @ 600–620 °C inlet
- Constant exhaust flow rate
- Exhaust temp. varied via heat exchangers

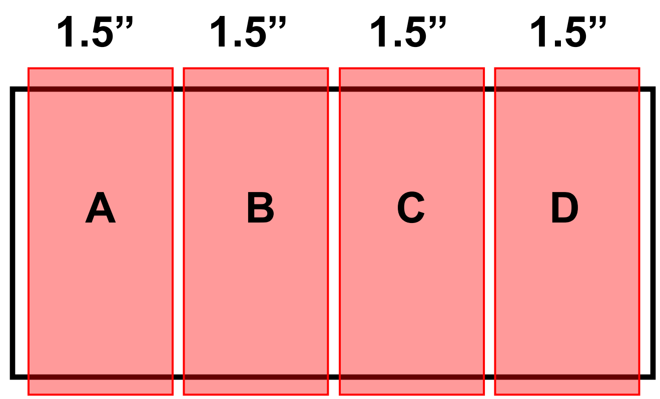
DPF Post-Mortem Analysis

- **DPF Sectioned**
  - (4) Axial sections: 1.5” long
  - (5) Radial samples: ~140 – 180 cells
  - (20) samples per DPF

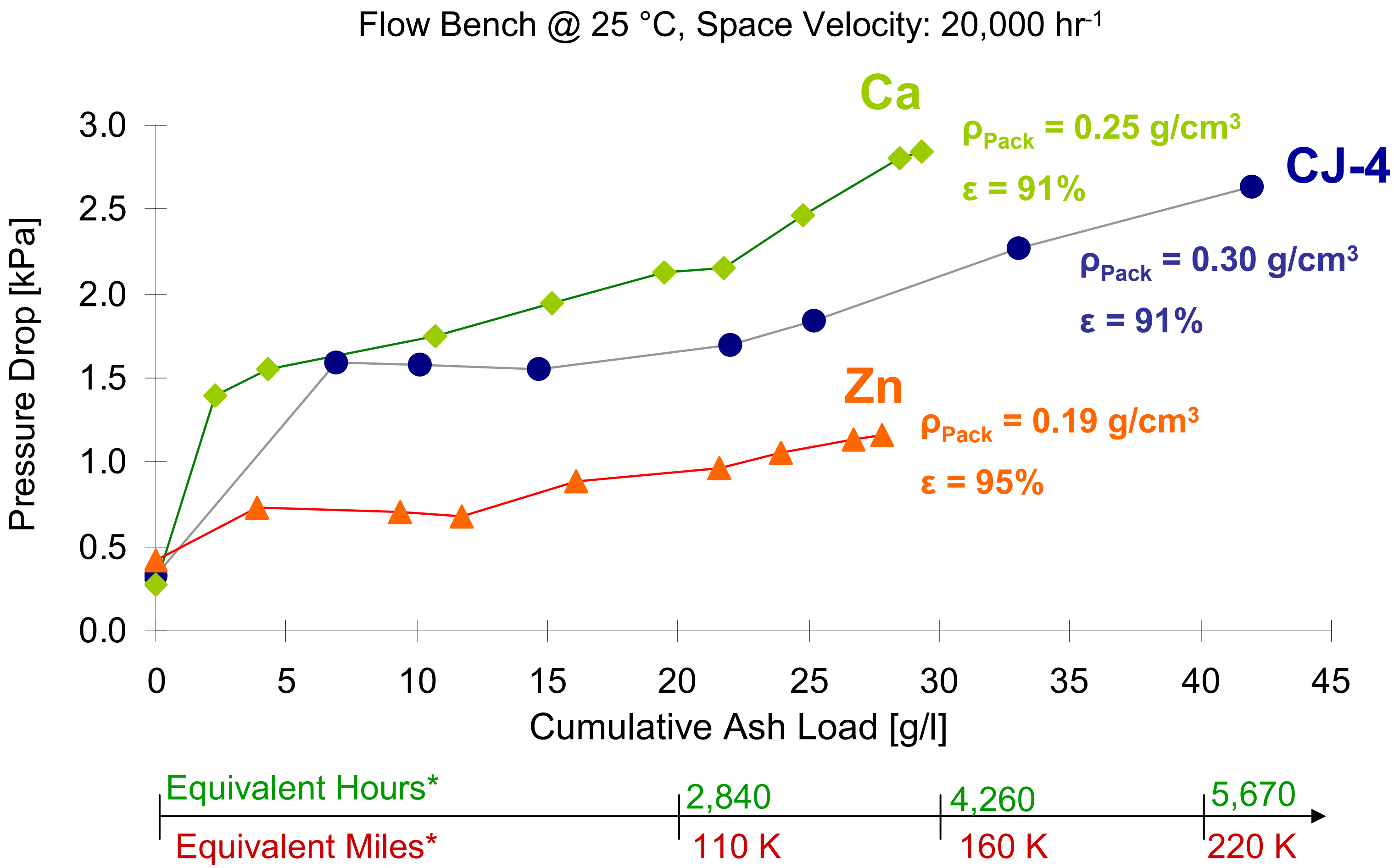


- **Sample Measurements**
  - Ash weight
  - Ash layer thickness and volume
  - Ash composition XRD, SEM-EDX





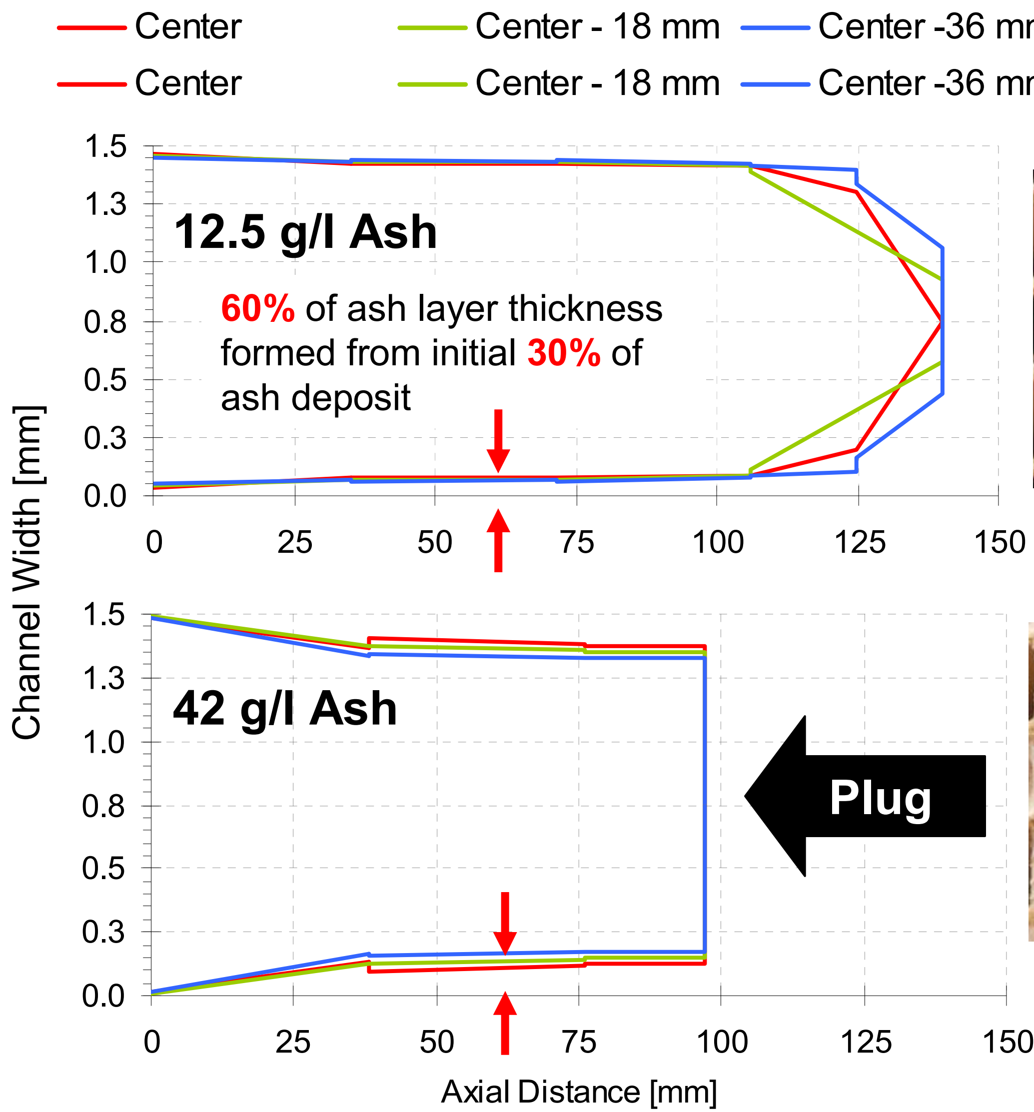
Individual Additive Effects on Pressure Drop (Ash)



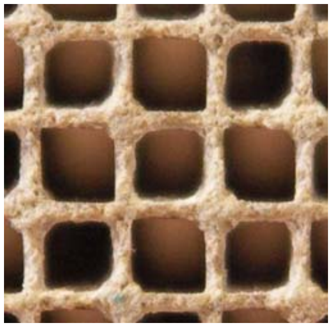
- Lubricant additive chemistry affects ash properties and pressure drop
- Ca-based ash shows much larger effect on pressure drop than Zn ash

*** Assumes: 15 g/hr avg. oil consumption, avg. speed of 40 mph, and full size DPF of 12 L volume**

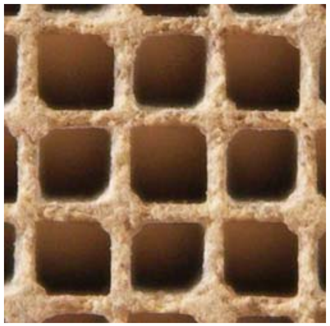
Ash First Accumulates Along DPF Channel Walls



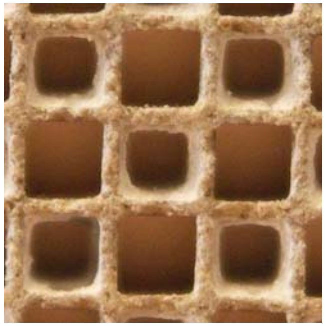
57 mm



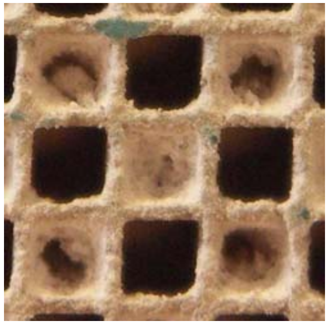
133 mm



57 mm

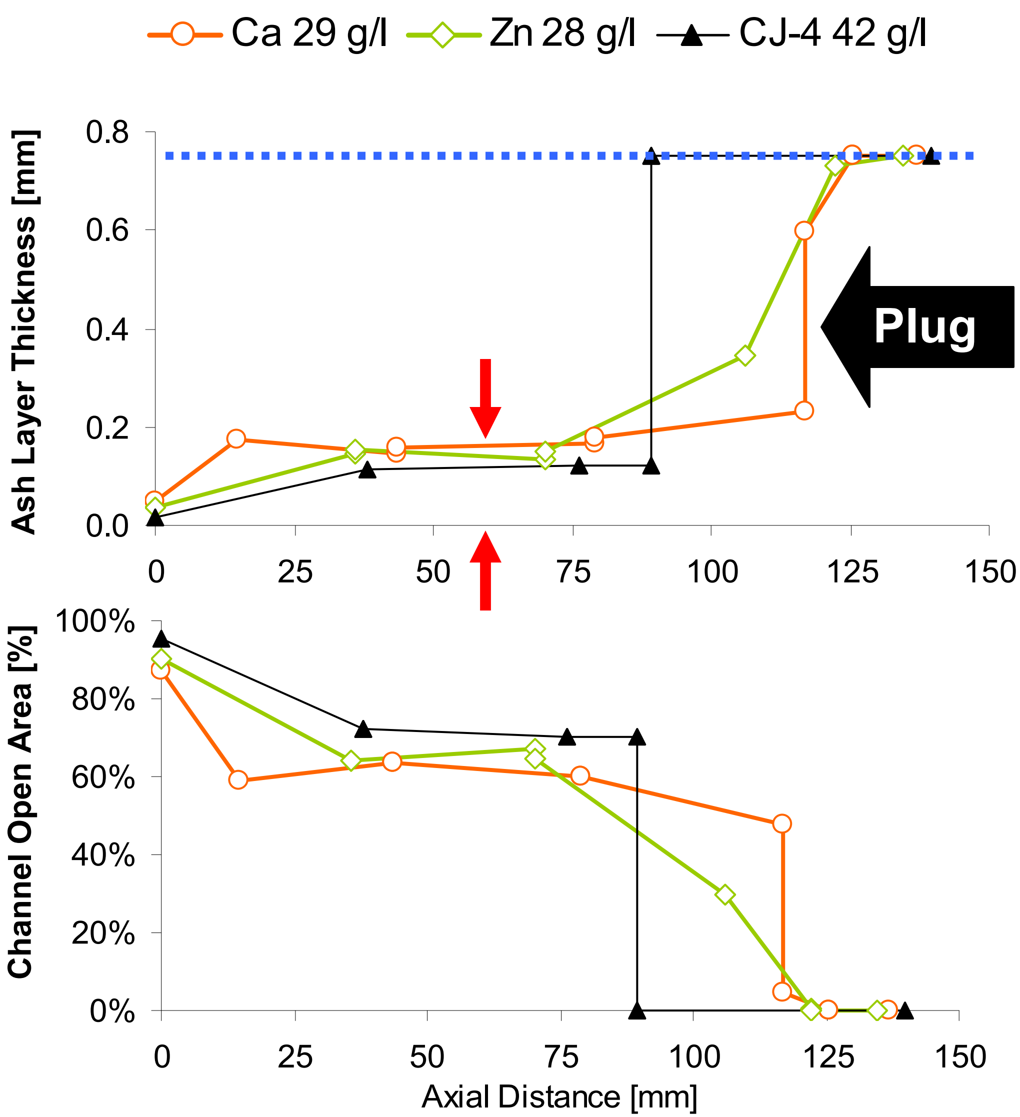


133 mm



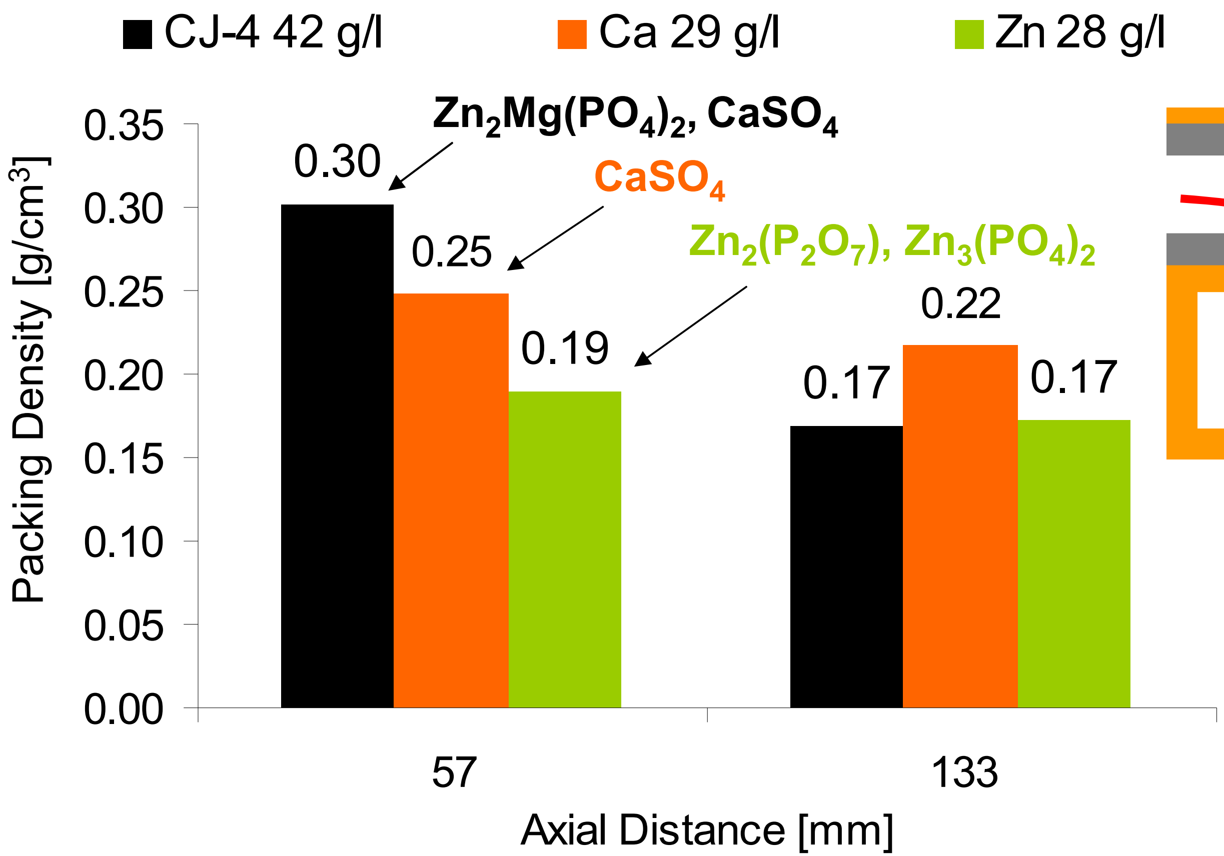
- **Ash preferentially deposited in end-plug during later stages of ash build-up**

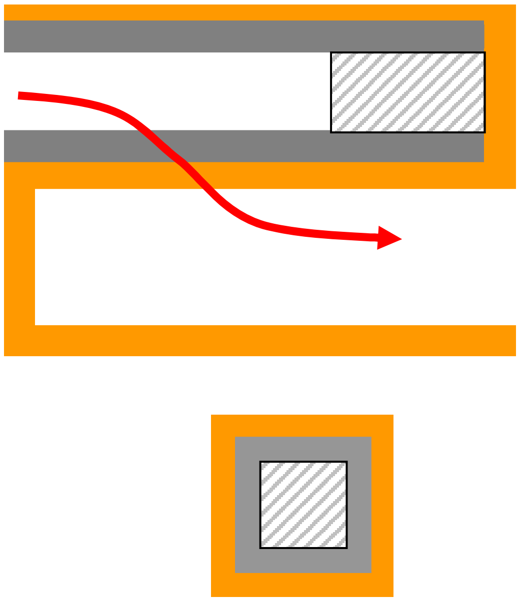
Ash Layer Thickness Profiles Similar for All Lubricants



- **Ash Layer Thickness**
  - Ca and Zn ash show slightly thicker ash layer vs. CJ-4 oil despite lower ash levels
  - Ash deposits on walls before forming ash plug
- **Channel Open Area**
  - Channel area reduced 27% to 40%
  - Despite **similar deposit profiles**, Zn ash showed much lower pressure drop
  - Ash properties (K) affected by lube chemistry

Additive Chemistry Affects Ash Packing Density

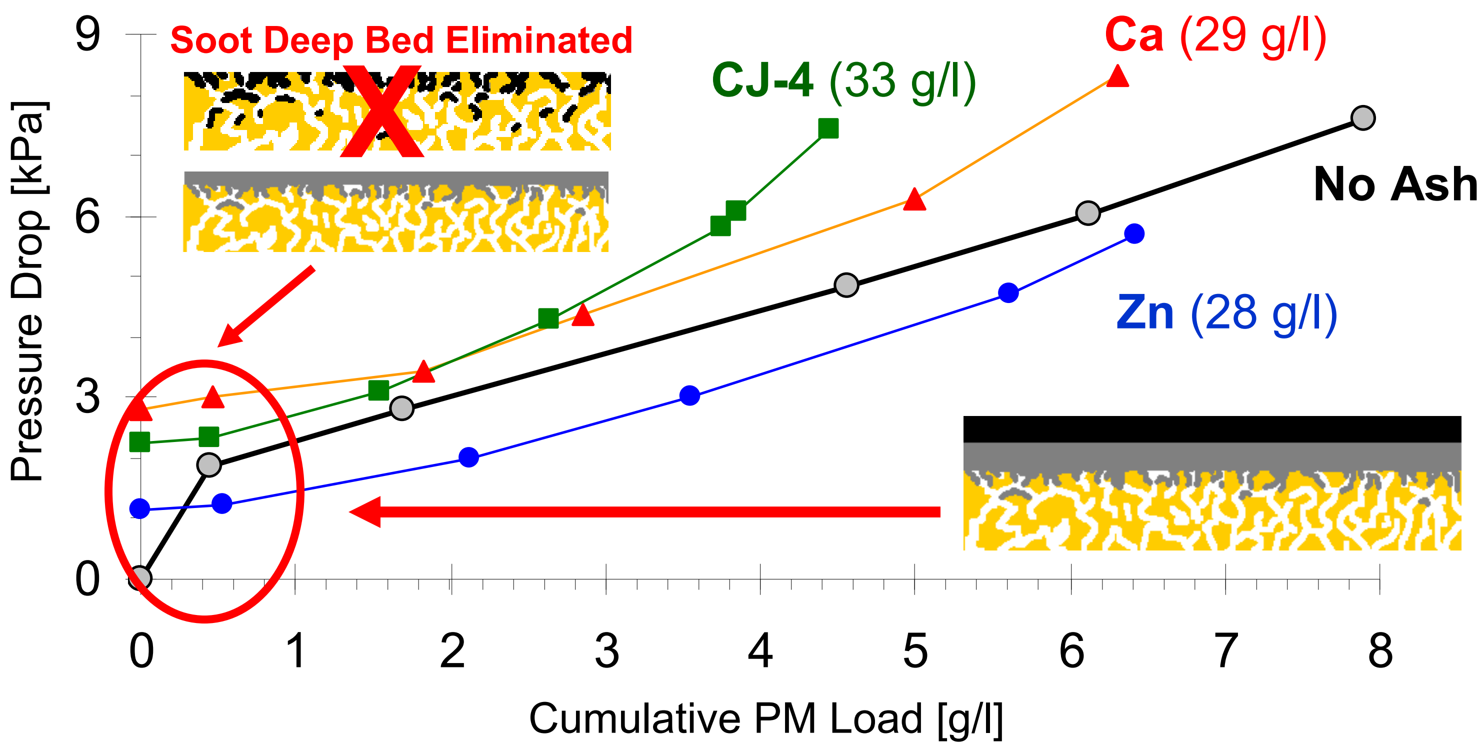




- **Significant difference in packing density for ash along wall vs. plug**
  - Ash in end-plug less densely packed than ash along channel wall for CJ-4 oil
  - Variation in packing density less pronounced for Ca and Zn ash

Individual Additive Effects on Pressure Drop (Ash+Soot)

Flow Bench @ 25 °C, Space Velocity: 20,000 hr^{-1}



- Ash loaded DPFs exhibit non-linear pressure drop response to PM loading
- Ash decreases pressure sensitivity to low PM loads **<0.5 g/l**
- Ash increases pressure sensitivity to PM loads **>3.0 g/l**

Individual Additive Effects: Pressure Drop Sensitivity

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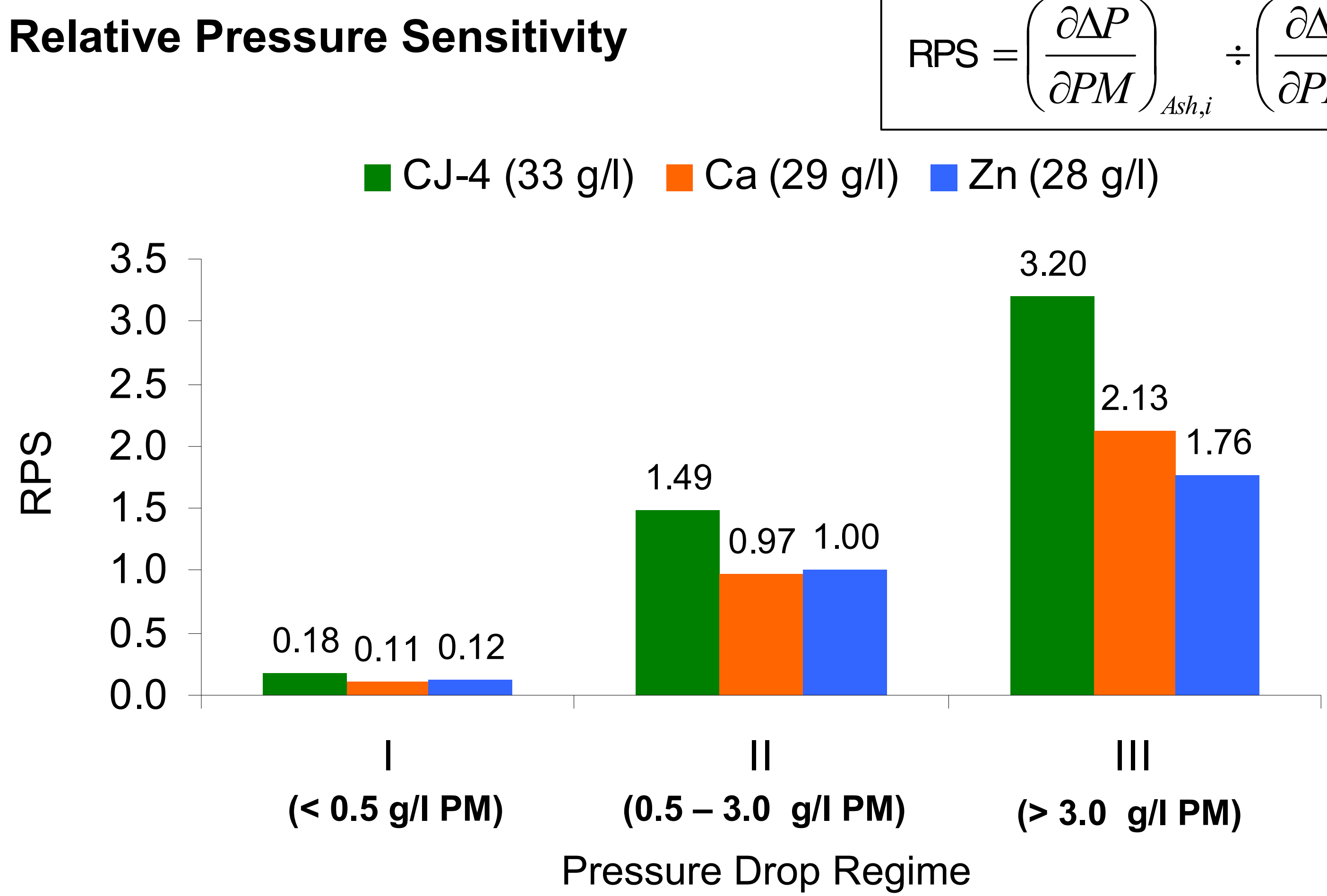
$$\text{RPS} = \left(\frac{\partial \Delta P}{\partial PM}\right)_{Ash,i} \div \left(\frac{\partial \Delta P}{\partial PM}\right)_{Clean,i}$$



- Ca and Zn base oils show similar effects on pressure drop sensitivity, particularly for soot loads < 3.0 g/l
- Fully-formulated CJ-4 oil shows largest effect on pressure drop sensitivity

Ash and Soot Effects on Fuel Economy (CJ-4)

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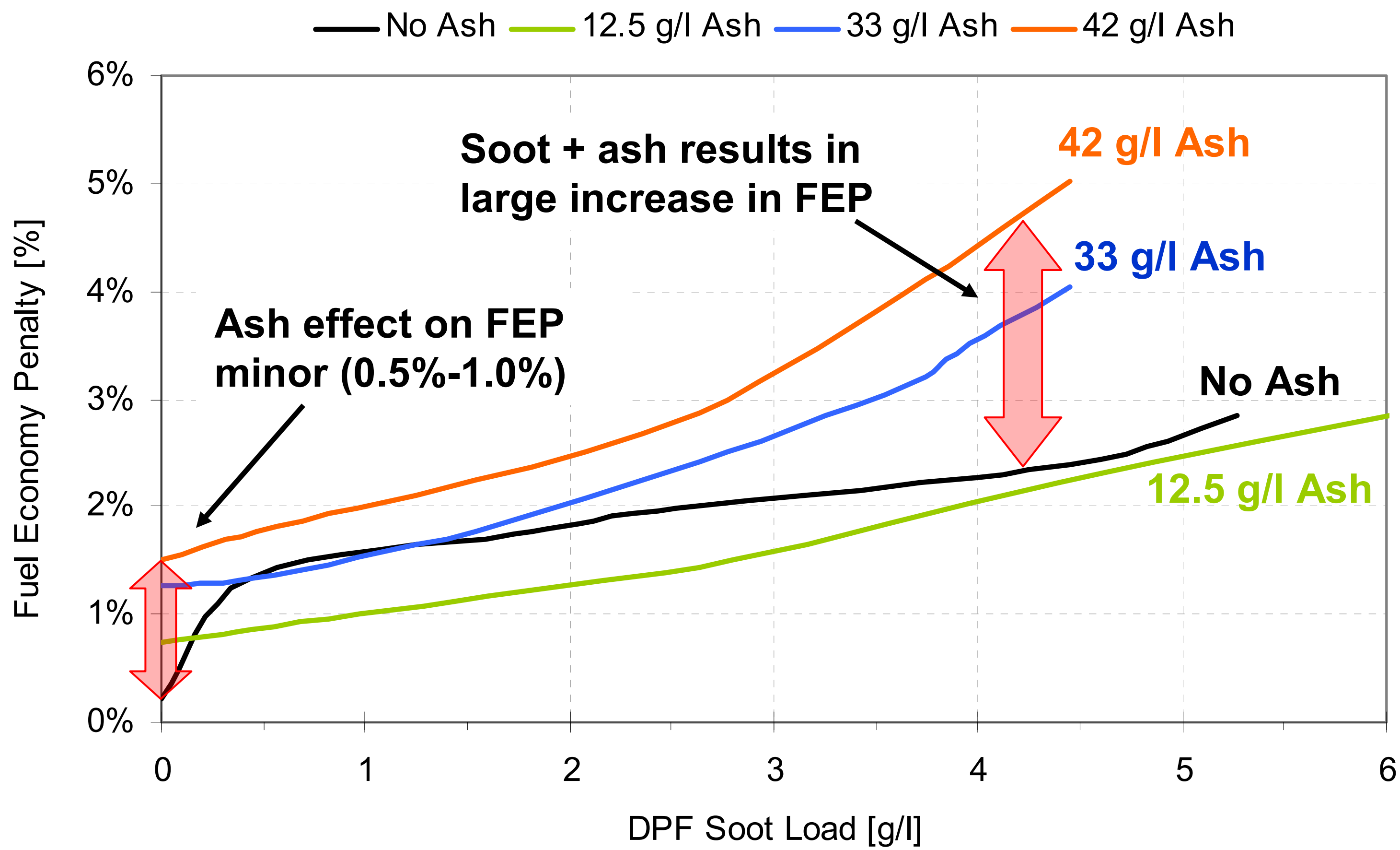
Estimated Euro III – 13 Mode Cycle Average



- FEP estimate assumes adiabatic expansion of ideal gas through turbo
- Model inputs from experimental data
- Soot + ash results in largest increase in FEP

$$FEP \approx \frac{\Delta W_{turbo}}{W_{engine}} \times 100$$

Conclusions

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Additive Chemistry Effects on DPF Pressure Drop

- Ash accumulation is a dynamic process – Ash first primarily accumulates along channel walls before forming end plugs at the back of the DPF
- Increase in DPF pressure drop **2X** more severe with **Ca** ash than **Zn**
- Similar ash properties and pressure drop trends between CJ-4 oil and Ca oil indicate **$CaSO_4$** may be most detrimental ash component

Ash + Soot Effects on DPF ΔP and Fuel Economy

- Ash decreases pressure sensitivity to low soot loads (<0.5 g/l)
- Ash increases pressure sensitivity for soot loads > 3g/l
- Increase in pressure drop sensitivity most severe with fully-formulated oils
- Ash alone results in only small increase in backpressure and fuel economy
- Soot accumulated in ash-loaded DPF results in largest FEP

Acknowledgements

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- NGK	- Oak Ridge National Lab	- Süd-Chemie
- Valvoline	- *Ford*	- *Lutek*

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