Key Parameters Affecting DPF Performance Degradation and Impact on Lifetime Fuel Economy

October 4, 2011

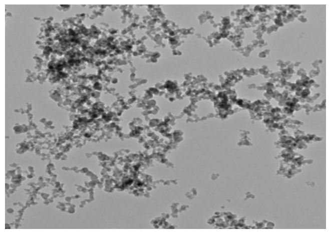
Alexander Sappok, Carl Kamp, Iason Dimou, Sean Munnis, Victor W. Wong

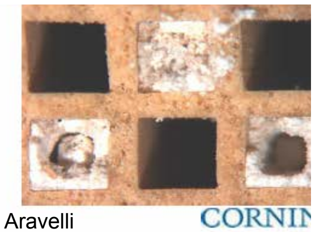
Massachusetts Institute of Technology
Sloan Automotive Laboratory
Cambridge, MA

U.S. DEPARTMENT OF ENERGY
DEER 2011 DETROIT
Directions in Engine-Efficiency and Emissions Research Conference

Ash Accumulation Reduces DPF Life and Engine Efficiency

Lube/ Fuel → Engine-Out Emissions → DPF Ash Accumulation → DPF ΔP Catalyst → Efficiency & DPF Life

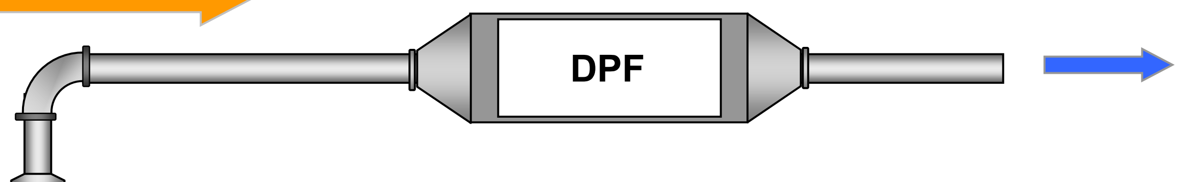




Source: K. Aravelli

Engine-Out Ash Emissions

FEP → $f(\Delta P)$



Lubricant Additives

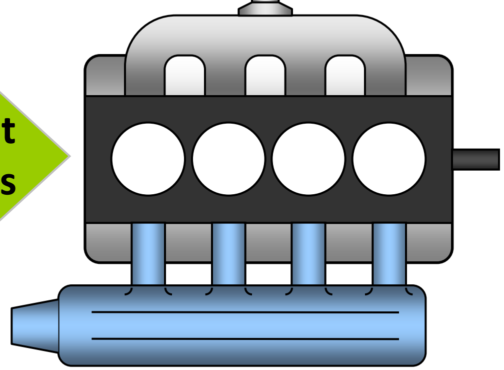
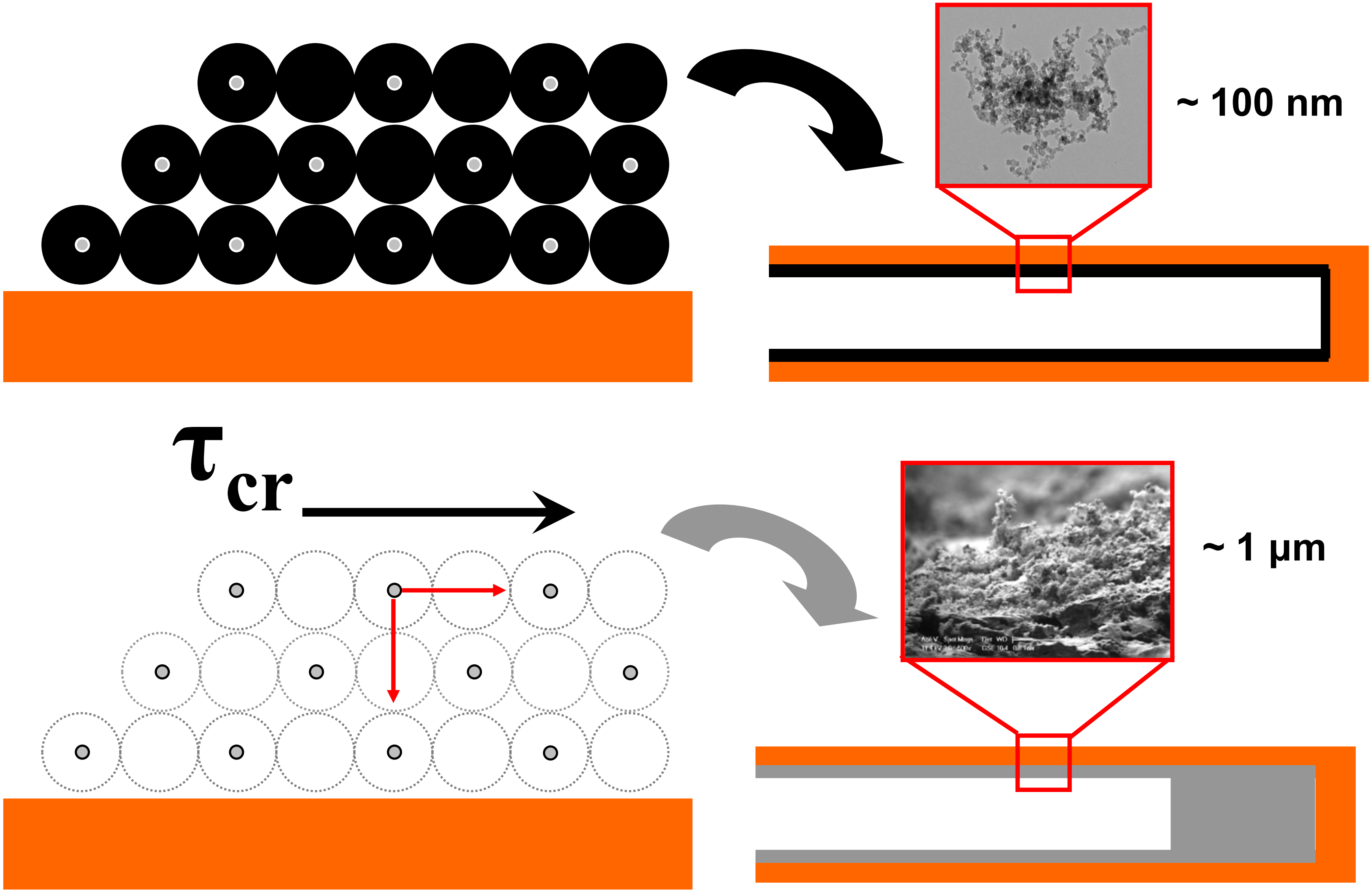


Image: Adapted from ORNL

DPF Ash Accumulation

- Incoming ash/soot particles
- Ash composition
- Exhaust conditions/Regeneration
- DPF design parameters
- DPF operating history important

Ash Accumulation and Deposit Formation Differs from PM!



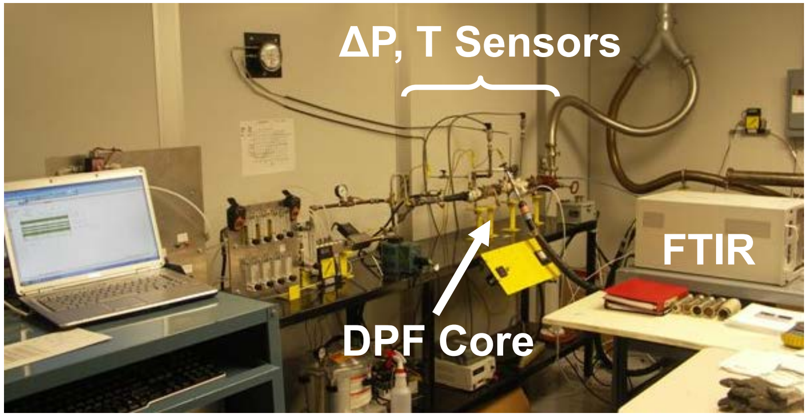
Experimental Apparatus – DPF Performance Testing

SLOAN AUTOMOTIVE LABORATORY

Cummins ISB 300

- Variable geometry turbocharger
- Cooled EGR
- Common rail fuel injection
- Fully electronically controlled
- Gaseous and PM emissions measurement systems

DPF Bench Reactors

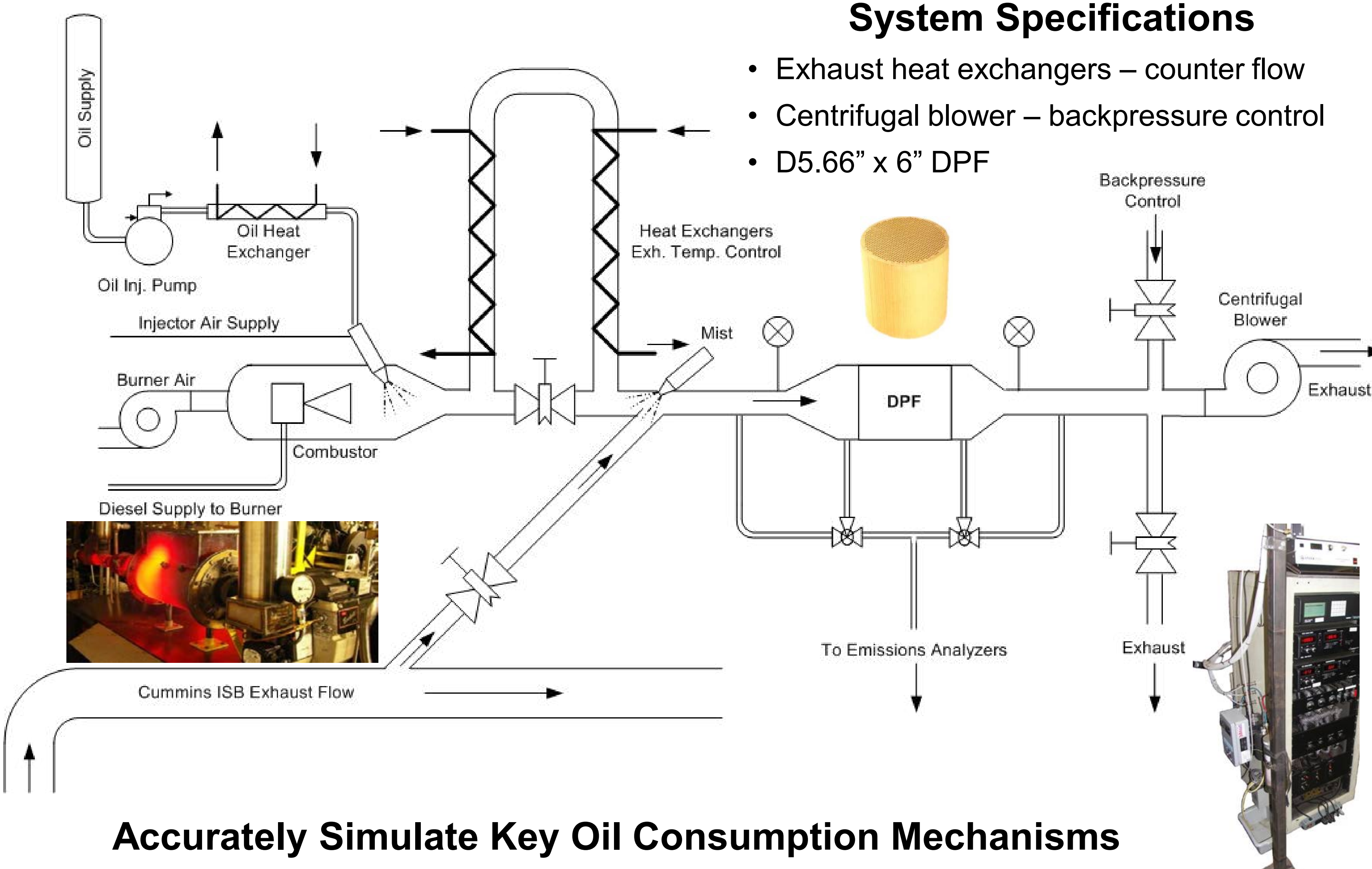


Accelerated Ash Loading

Accelerated Ash Loading System

System Specifications

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

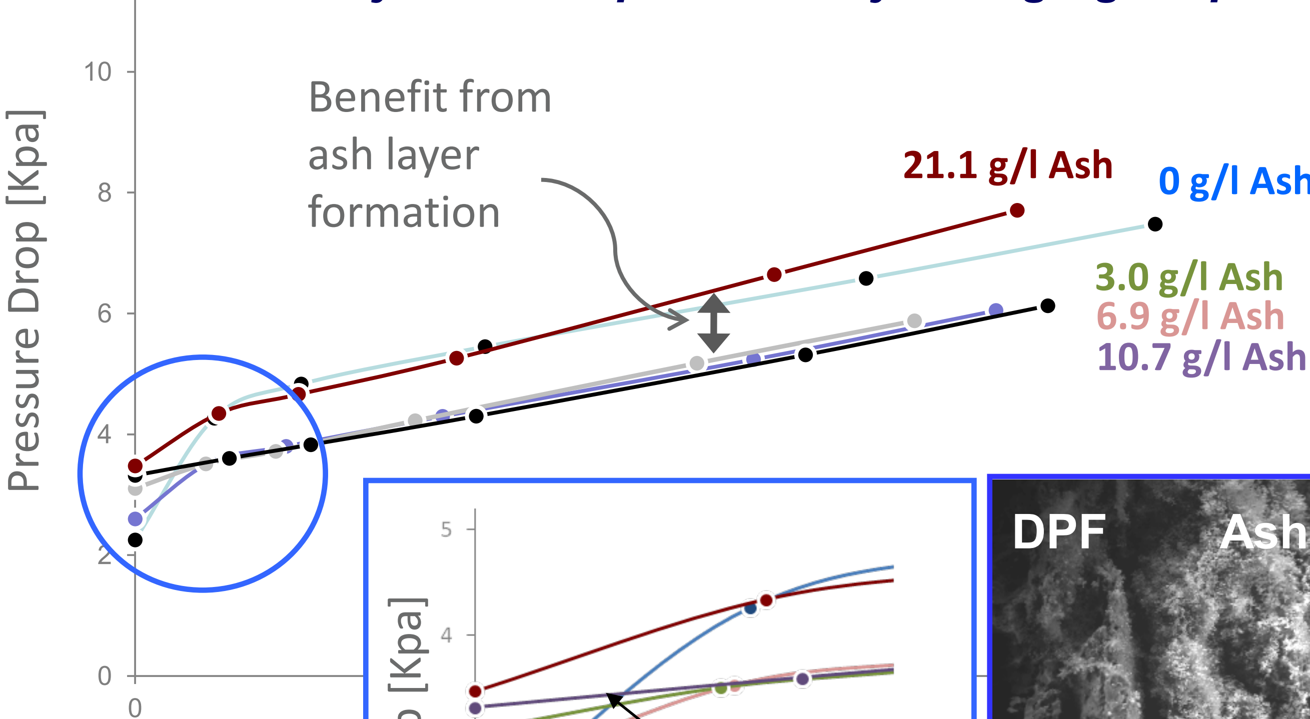


Accurately Simulate Key Oil Consumption Mechanisms

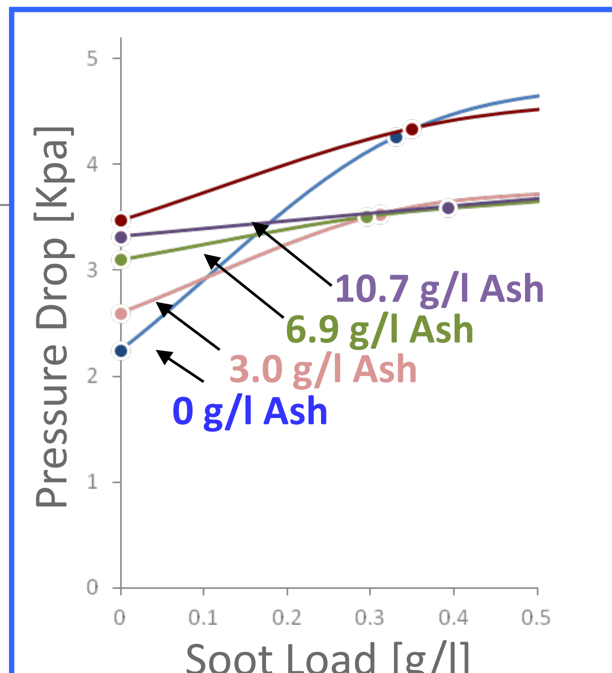
- Each parameter independently variable
- Precise control of quantity and characteristics of ash generated

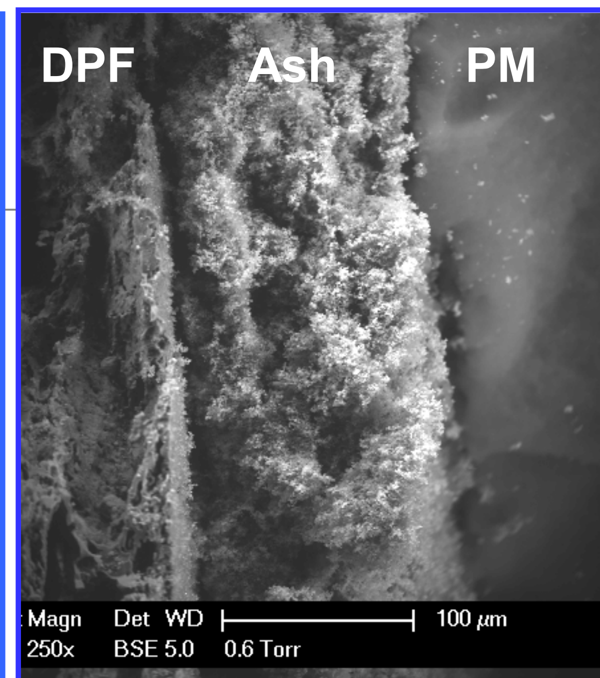
Initial Ash Deposition and Layer Formation

Ash layer build-up evident by changing ΔP profiles.



Ash layer not fully established until 10 g/L or ~ 50,000 miles

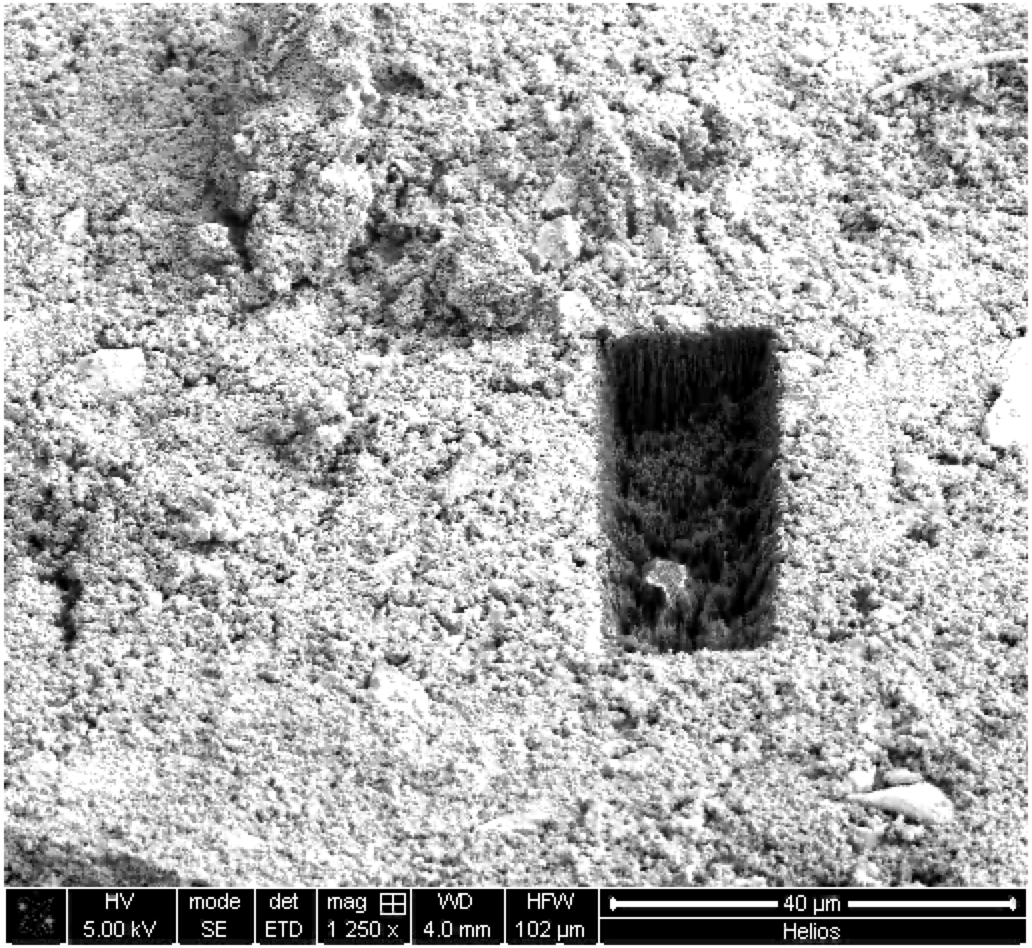




Ash – PM Layer Interface Clearly Defined

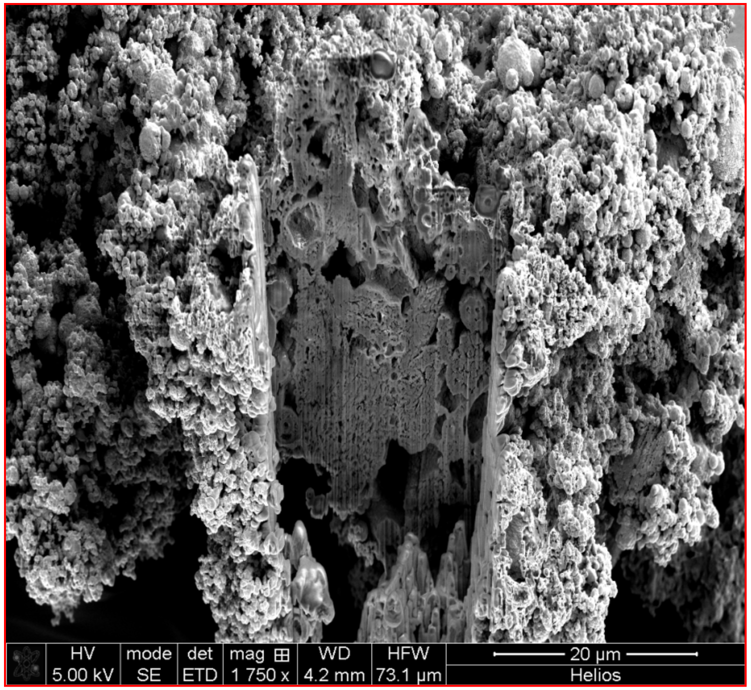
SLOAN AUTOMOTIVE LABORATORY

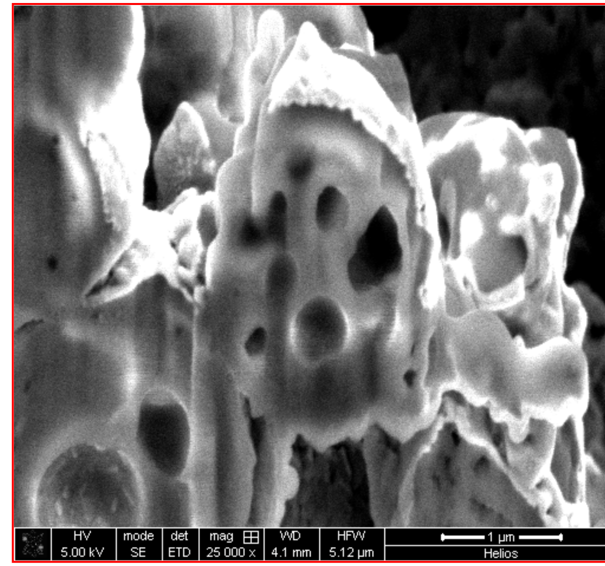
Focused Ion Beam (FIB) Milling Coupled with SEM

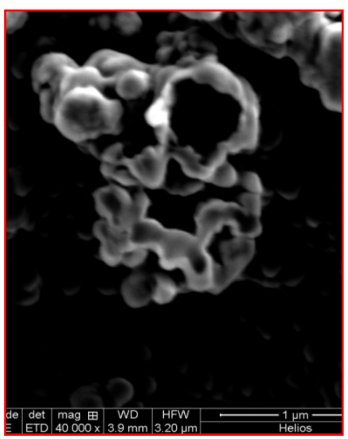


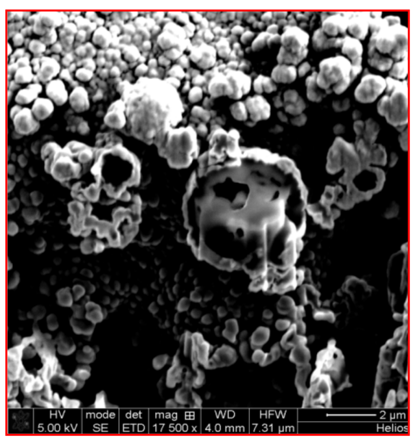
Unlike PM depth filtration in DPF surface pores, very little soot penetrates into ash layer.

Ash Primary Particles Exist as Porous Shells









Multiple length scales for porosities in ash layer and primary particles.

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

$$K = f\left(\varepsilon, \overline{D}_P\right)$$

$$\varepsilon = 1 - \frac{\rho_{Packing}}{\rho_{Theoretical}}$$

Potential to improve ash packing!

Additive Chemistry Impact on Ash Properties

Lubricant matrix all formulated to 1% sulfated ash, except base oil.

Lubricant	Ca *ppm*	Mg *ppm*	Zn *ppm*	P *ppm*	S *ppm*	B *ppm*	Mo *ppm*
Base	*<1*	*<1*	*<1*	*8*	*60*	*1*	*<1*
Base + Ca	2,928	5	<1	2	609	3	<1
Base + Mg*	<1	2,070	<1	<1	460		<1
Base + ZDDP	<1	<1	2612	2,530	6,901	1	<1
Base, Ca+ZDDP*	2480	<1	1280	1,180	2,750		<1
Base, Mg+ZDDP*	<1	1730	1280	1,180	2,840		<1
Commercial CJ-4	1,388	355	1,226	985	3,200*	586	77

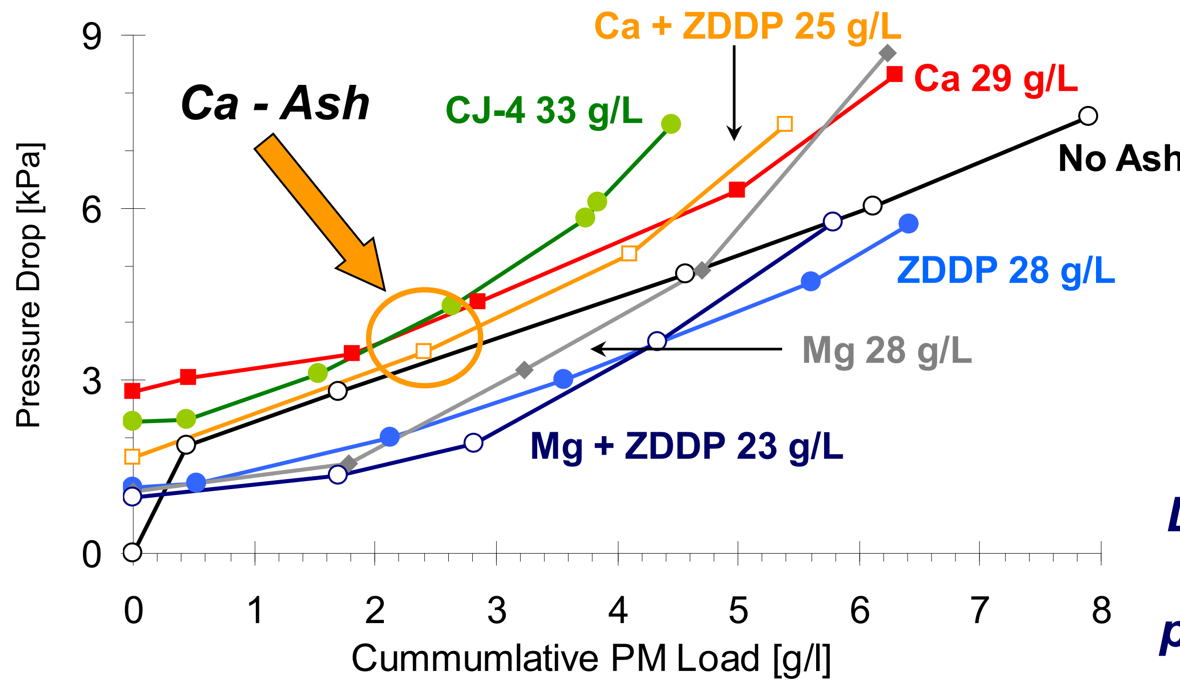
Composition of ash directly related to lubricant additive chemistry.

Major Ash Components		Density *g/cm³*	Melting Point *°C*	Description
$CaSO_4$	Calcium Sulfate	2.96	1,460	Sinters/Decomposes ~1,250 °C
$CaZn_2(PO_4)_2$	Calcium Zinc Phosphate	3.65		
$Zn_2(P_2O_7)$	Zinc Pyrophosphate	3.75		Sintering begins ~ 800 °C
$Zn_3(PO_4)_2$	Zinc Phosphate	4.00	900	Sintering begins ~ 800 °C
$Zn_2Mg(PO_4)_2$	Zinc Magnesium Phosphate	3.60		
MgO	Magnesium Oxide	3.58	2,832	
MgSO4	Magnesium Sulfate	2.66	1,124	Decompostion 900-1,100 °C

Ash Chemistry Impacts Ash Properties and DPF ΔP

SLOAN AUTOMOTIVE LABORATORY

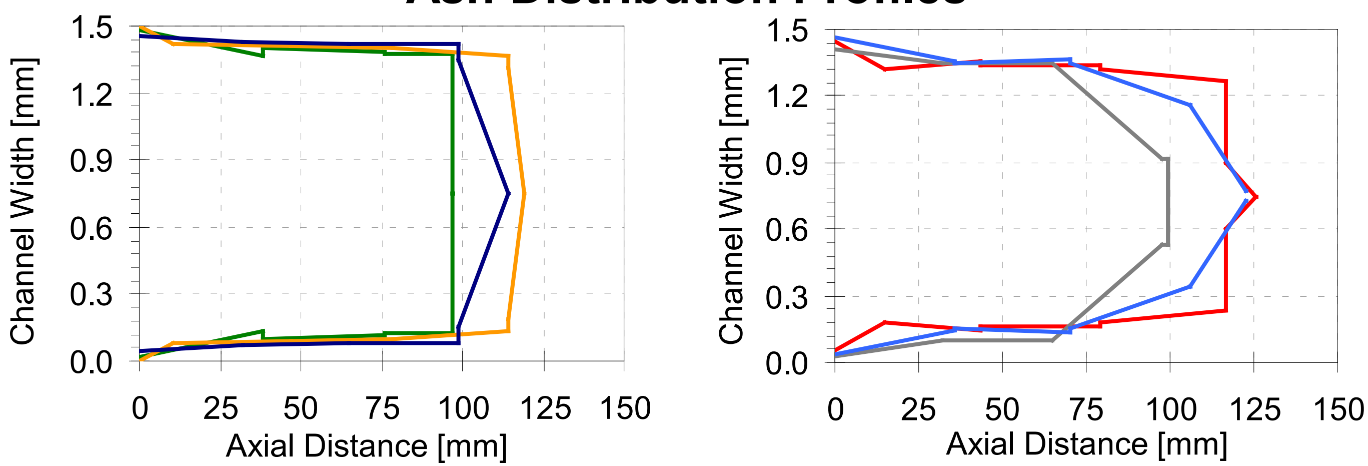
Flow Bench @ 25 C, Space Velocity: 20,000 hr^{-1}



Cordierite 200/12

Differences in DPF ΔP due to ash properties (ρ, ε, D_p)

Ash Distribution Profiles



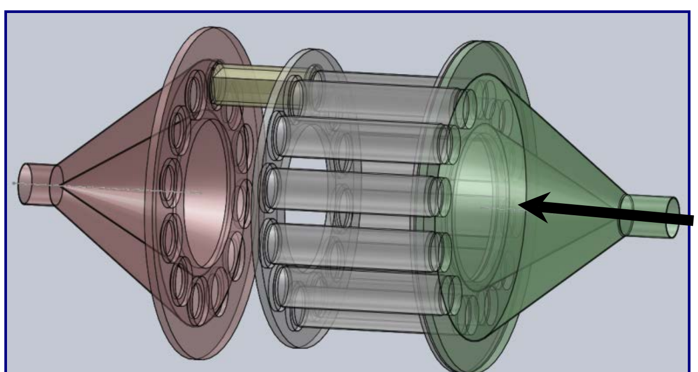
Sensitivity of DPF Design Parameters to Ash

Matrix	Porosity	Mean Pore Size
1st Trial	Low High	Low
2nd Trial	High	Low High
3rd Trial	Moderate	Low

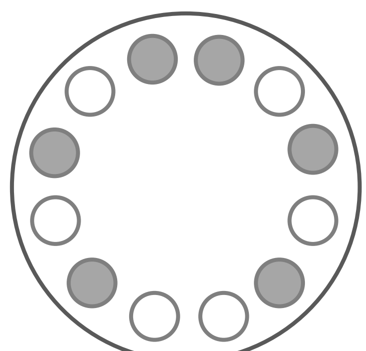
Additional DPF Parameters

- Filter/substrate materials
- DPF coatings and catalysts
- Filter geometry and cell configuration

Multi-Cartridge Filter Holder



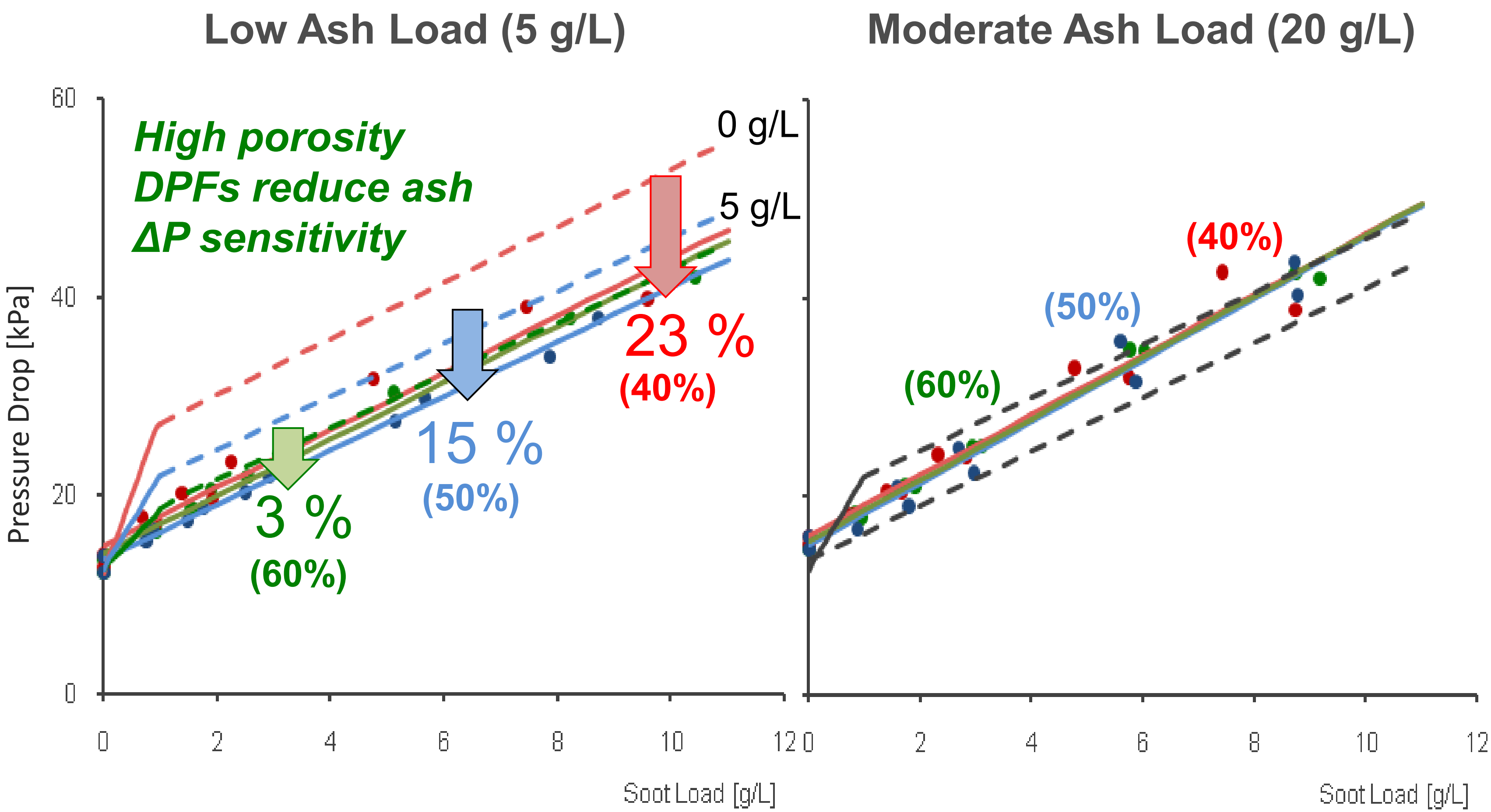
12 DPF Segments



Ash Loading

Sensitivity of DPF Porosity to Ash Accumulation Varies

SLOAN AUTOMOTIVE LABORATORY



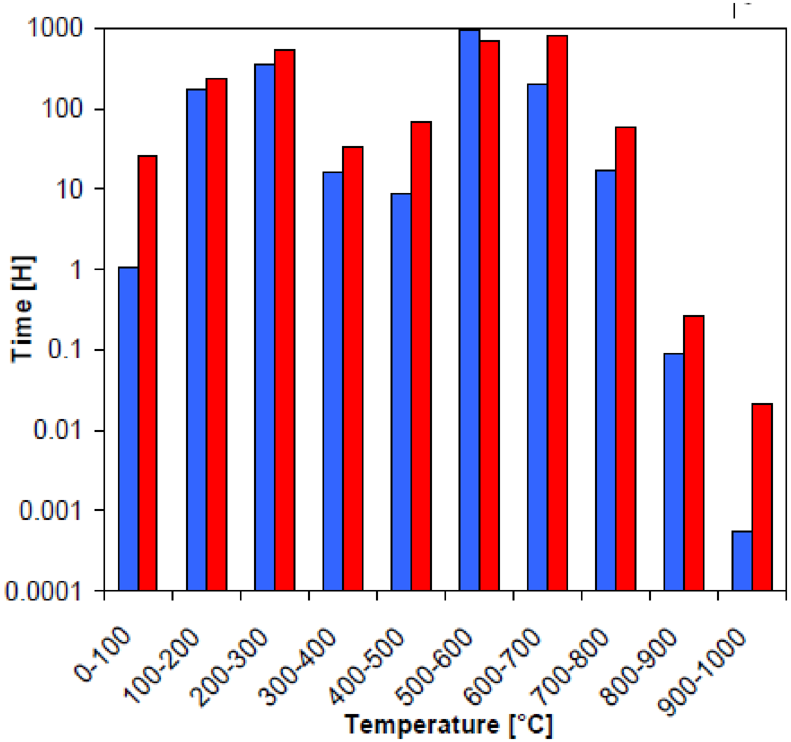
- Sensitivity of ΔP to ash accumulation increases with decreasing DPF porosity at low filter ash levels
- At high ash loads, ash dominates ΔP, which is insensitive to initial DPF porosity of filter, over range tested

Exhaust Conditions Also Continually Changing

SLOAN AUTOMOTIVE LABORATORY

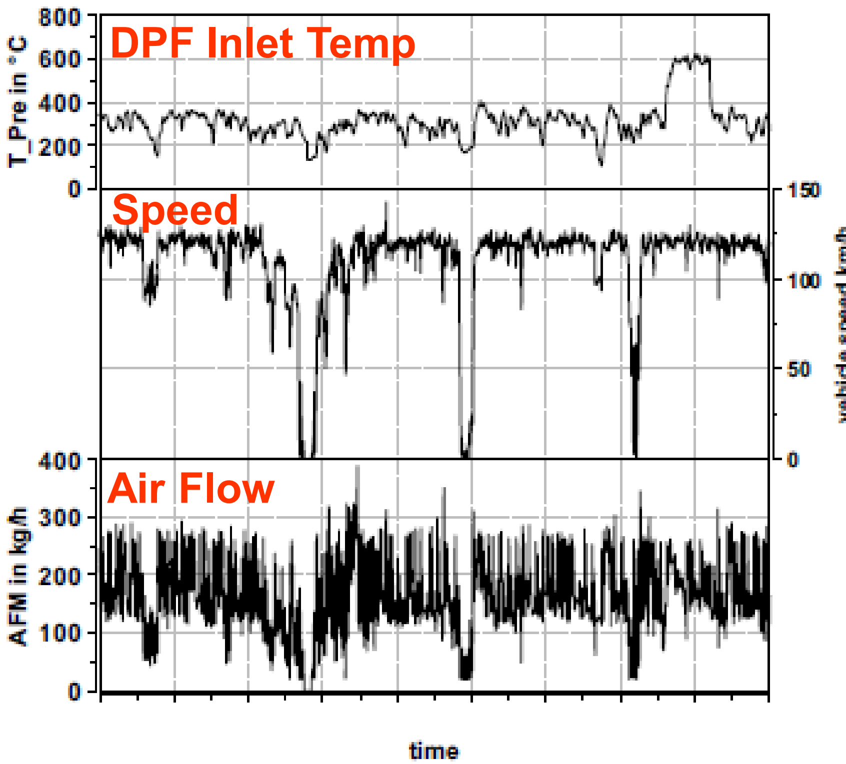
DPF Temperature Distribution

(300-420K Miles, HD Diesel)



Corning Deer 2006

Typical Highway Drive Cycle



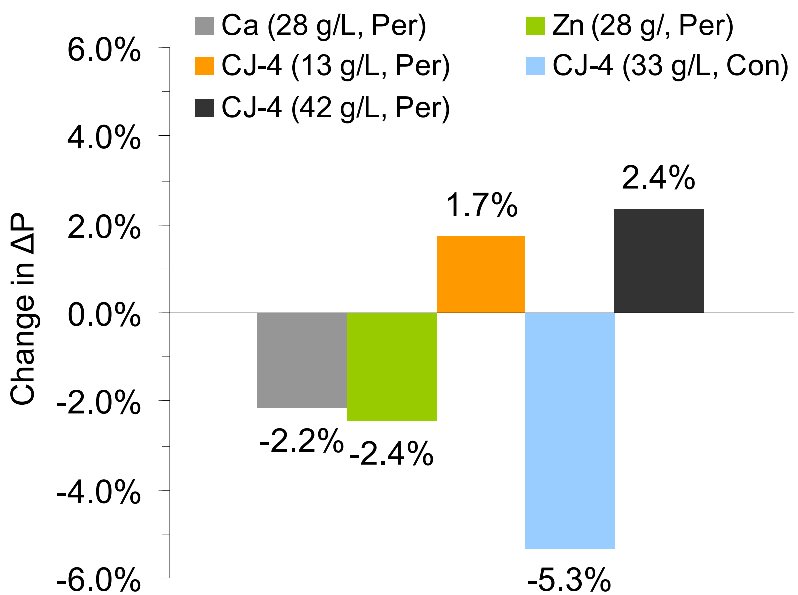
SAE 2009-01-1262

- Potential for short excursions above 700 C over DPF operating history
- Exhaust flow rates also vary considerably, even over highway drive cycle

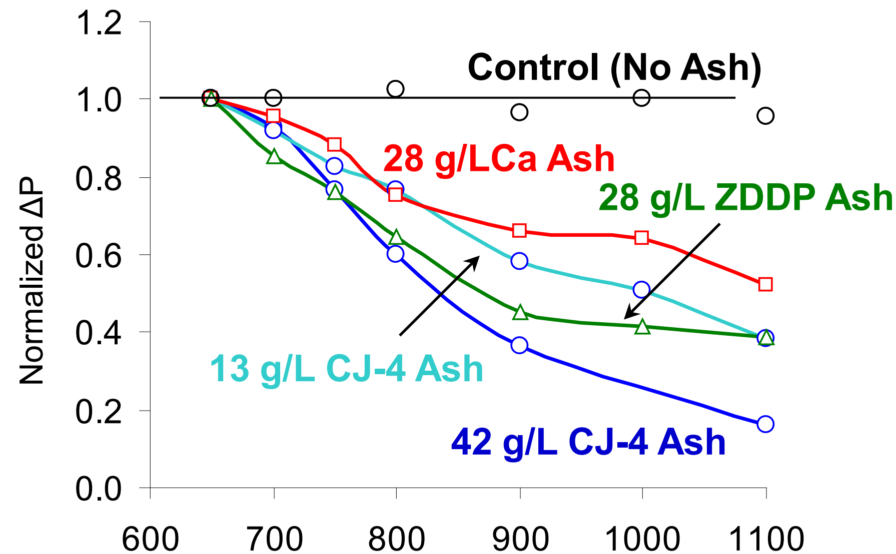
Elevated Temperatures Exert Large Effect on Ash Packing

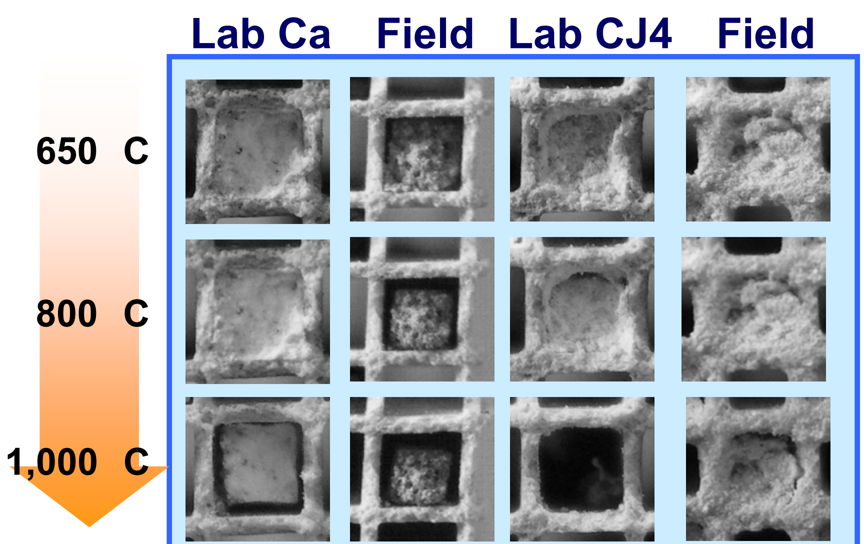
SLOAN AUTOMOTIVE LABORATORY

High Flow Exposure to 200,000 hr⁻¹



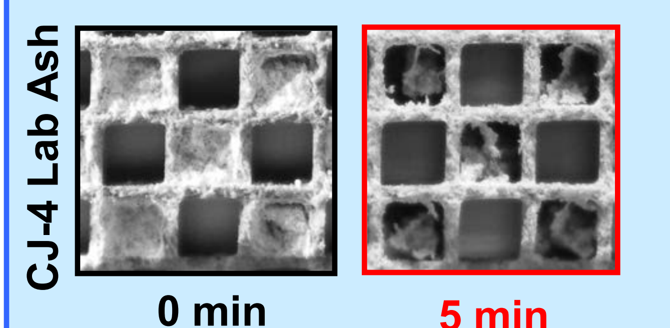
High Temperature Exposure





Ash Volume Reduction Fast

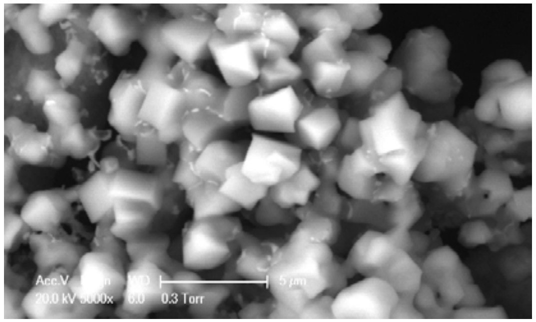
DPF core heated to 880 C
in 5 min, then quenched.

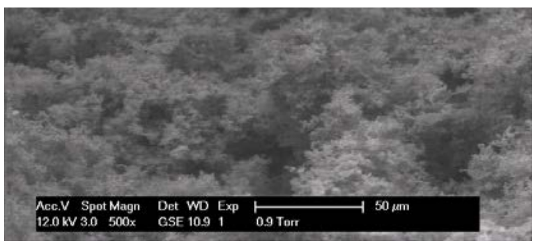


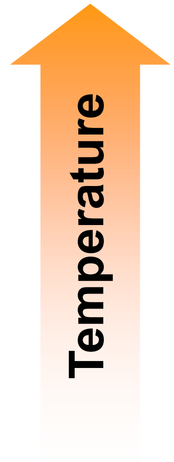
Chemical and Physical Changes in Ash at High Temps.

SLOAN AUTOMOTIVE LABORATORY

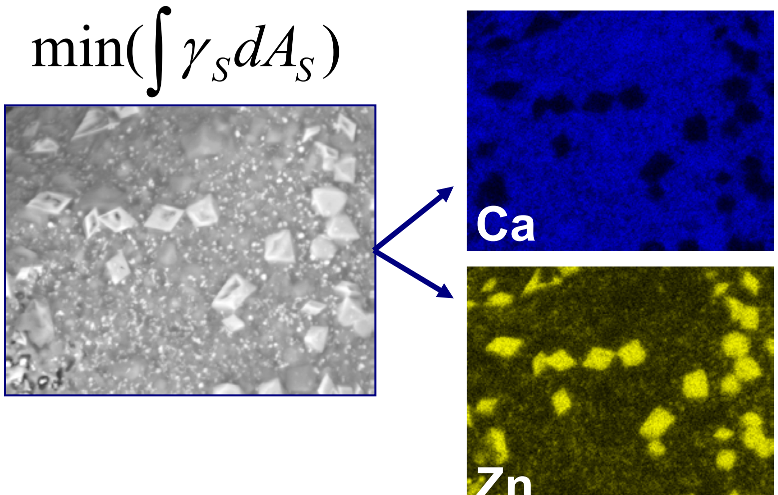
Equilibrium Crystal Structures formed at High Temperatures



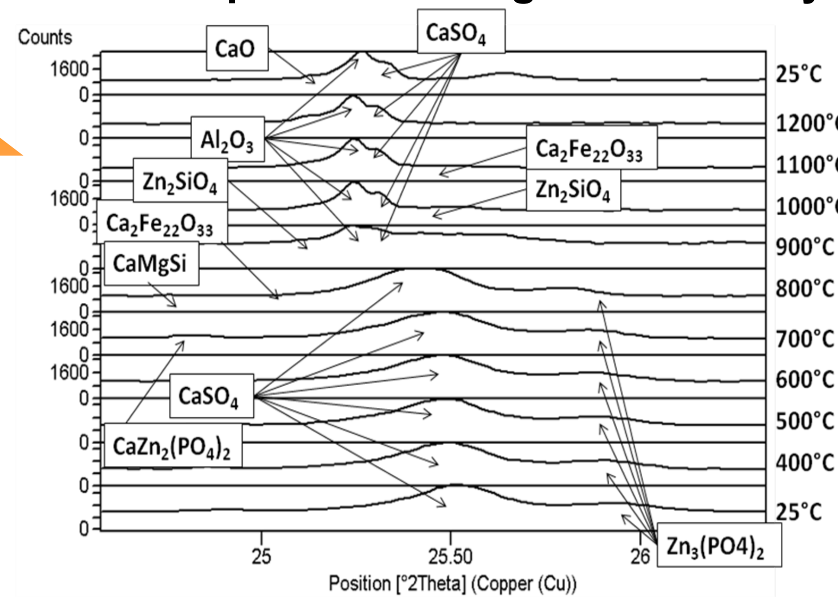


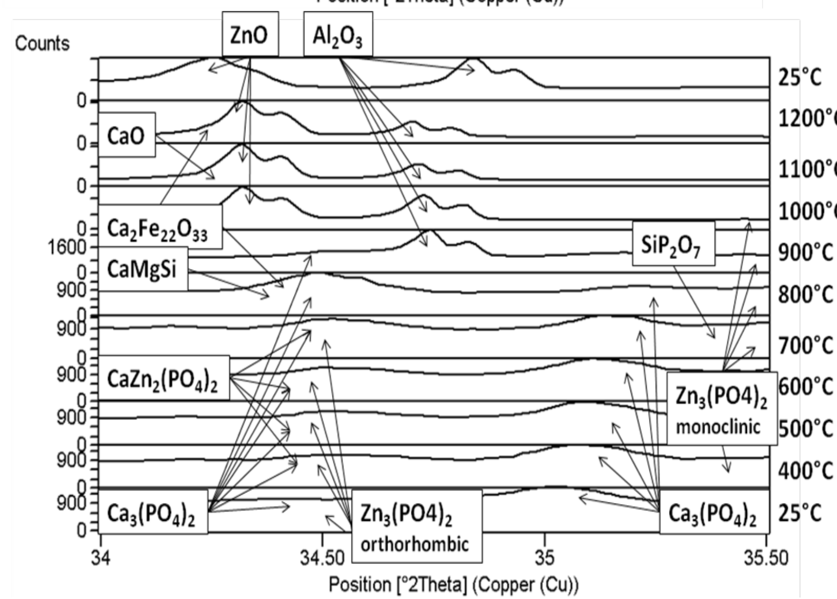


$$\min\left(\int \gamma_S dA_S\right)$$



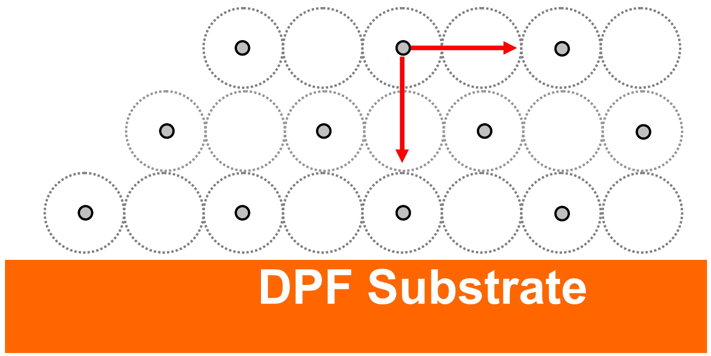
Ash Composition Changes Irreversibly





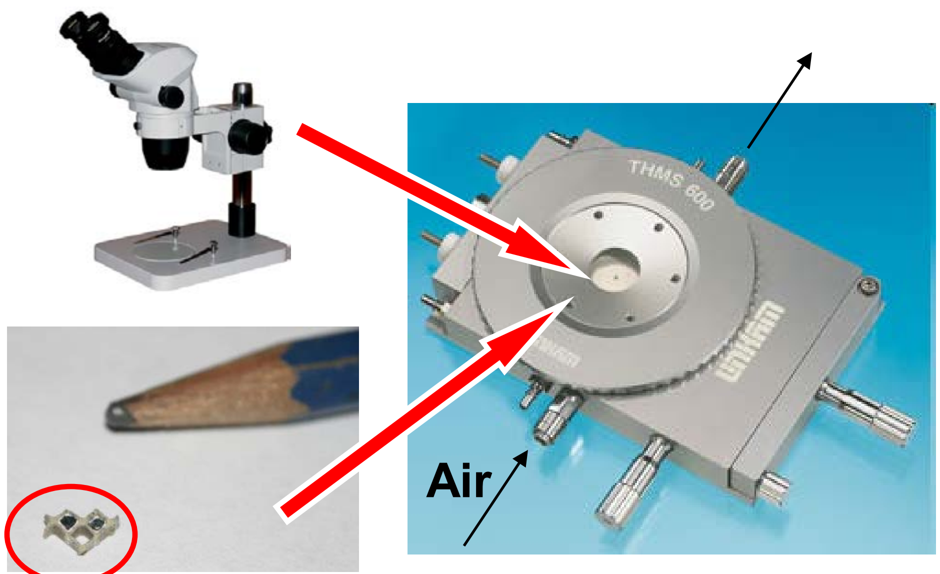
Optical Access System for DPF Regeneration Studies

- **Understand Influence of Regeneration on Ash Properties**
  - **Active/Passive strategies may impact ash agglomeration and mobility**
  - **Role of soot interactions with ash during regeneration important**

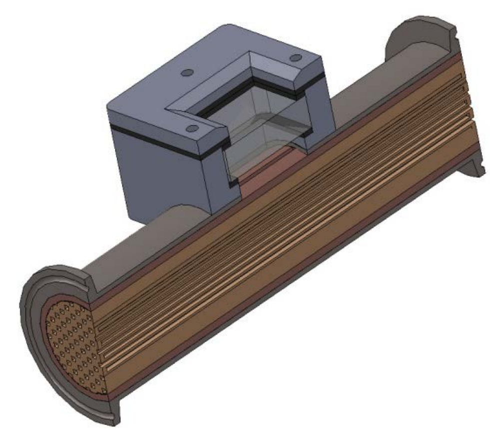


Regeneration Parameters

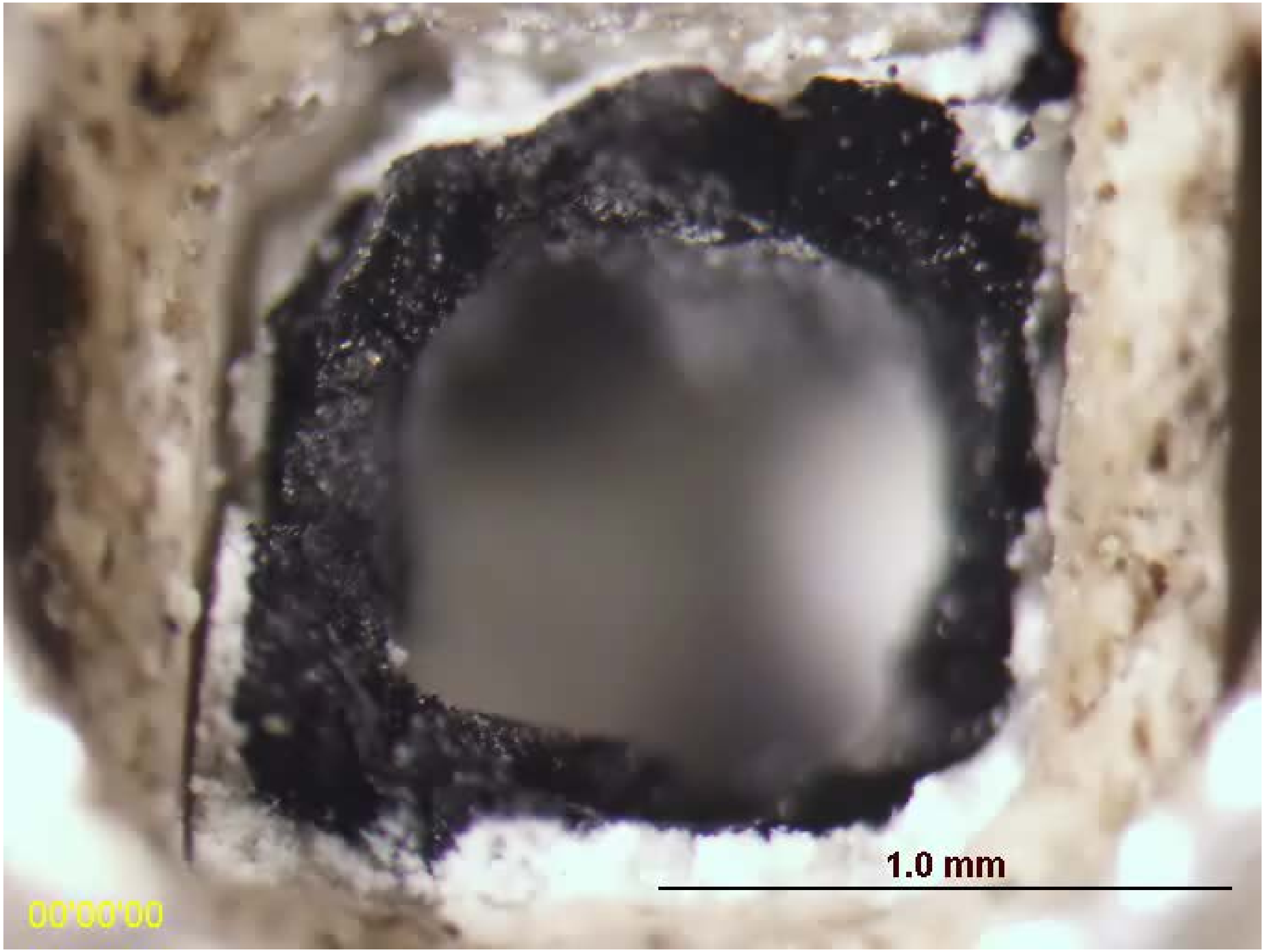
- Thickness of PM Layer
- Role of NO_2 from DOC vs. CDPF
- Temperature and flow conditions
- Catalysts interactions



2nd Generation



Video: PM Oxidation with Ash (DPF Cross Section)



Summary and Conclusions

SLOAN AUTOMOTIVE LABORATORY

Detailed understanding of all system parameters important to reduce impact of ash on DPF degradation and fuel efficiency.

I. Ash Build-Up: Ash loading of ~ 10 g/L or around 50,000 miles required to form fully-established ash layer.

II. Ash Morphology: Two porosity scales identified in ash layer and ash primary particles, which are themselves hollow.

III. Lube Chemistry: Ash properties and DPF pressure drop strong function of additive composition.

IV. Exhaust Conditions: Transient changes in temperature induce much larger variations in ash packing than high flow rates.

V. DPF Parameters: DPF pressure drop relatively insensitive to original substrate porosity following ash layer build-up.

VI. Regeneration Effects: Preliminary optical studies highlight importance of regeneration parameters but requires further study.

Acknowledgements

SLOAN AUTOMOTIVE LABORATORY

- **Research supported by: MIT Consortium to Optimize Lubricant and Diesel Engines for Robust Emission Aftertreatment Systems**
- **We thank the following organizations for their support:**

U.S. Department of Energy
Energy Efficiency and Renewable Energy

- Caterpillar	**- Chevron**		**- Cummins**
- Detroit Diesel	**- Infineum**		***- Komatsu***
- NGK	**- Oak Ridge National Lab**		**- Süd-Chemie**
- Valvoline	***- Ford***	***- Ciba***	***- Lutek***

- **MIT Center for Materials Science and Engineering**