Unraveling DPF Degradation using Chemical Tracers and Opportunities for Extending Filter Life

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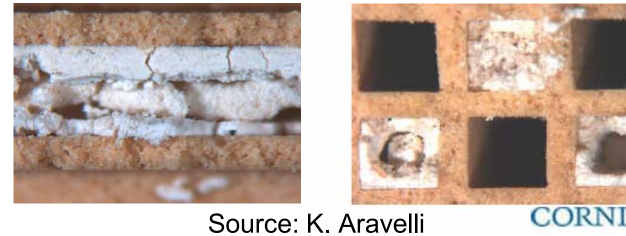
DIRECTIONS IN ENGINE-EFFICIENCY AND EMISSIONS RESEARCH CONFERENCE

Ash Impacts Diesel Particulate Filter Performance

Courtesy: E. Senzer



Source: K. Aravelli

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

After only 33,000 miles 50% of material trapped in DPF is ash.

**Assumes 6 g/L maximum DPF PM load prior to regeneration*

Time Scale

1. LONG Time Scale (~ 100's hours)

- Ash build-up process and distribution in DPF

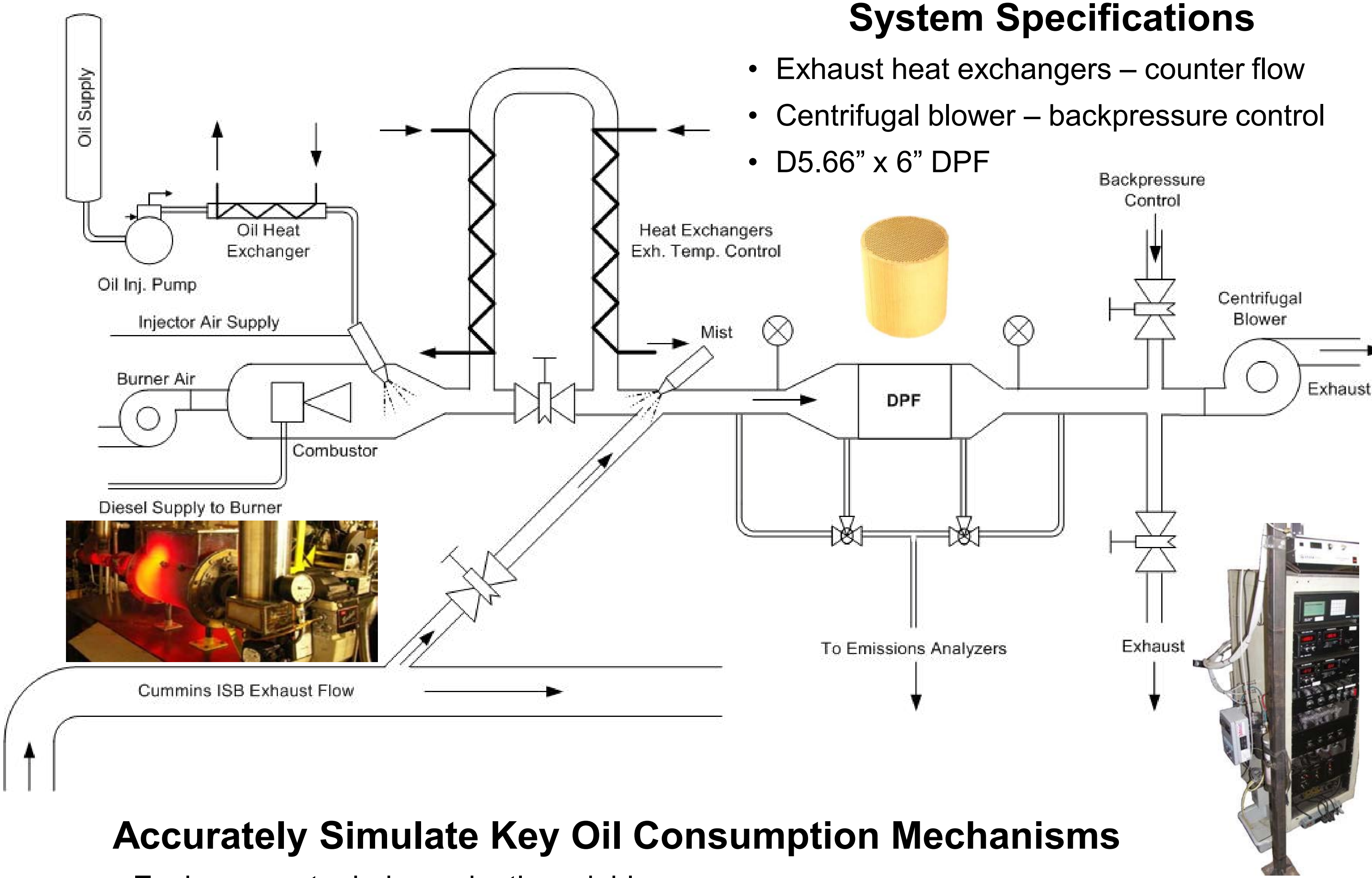
2. SHORT Time Scale (~ minutes)

- Changes in exhaust flow and temperature (engine control)

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

Experimental Apparatus – DPF Performance Testing

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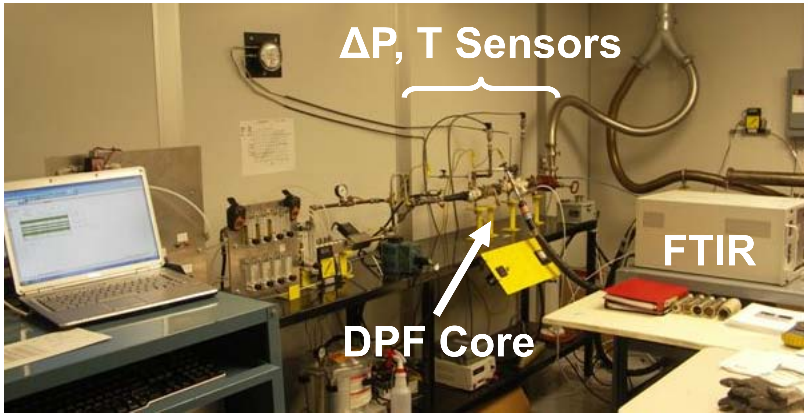
Cummins ISB used for DPF performance evaluation before and after ash loading tests on accelerated test rig.

Cummins ISB 300

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



DPF Flow Bench

- Core samples: D1” x 6”
- 200,000 hr^{-1} maximum flow
- 700 C maximum gas temperature
- Air or simulated exhaust

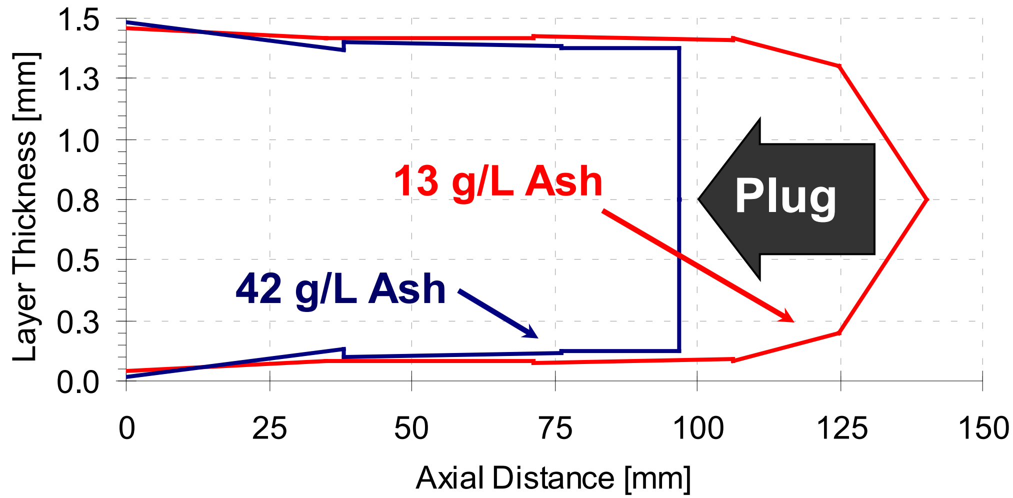
Ash Deposit Build-Up

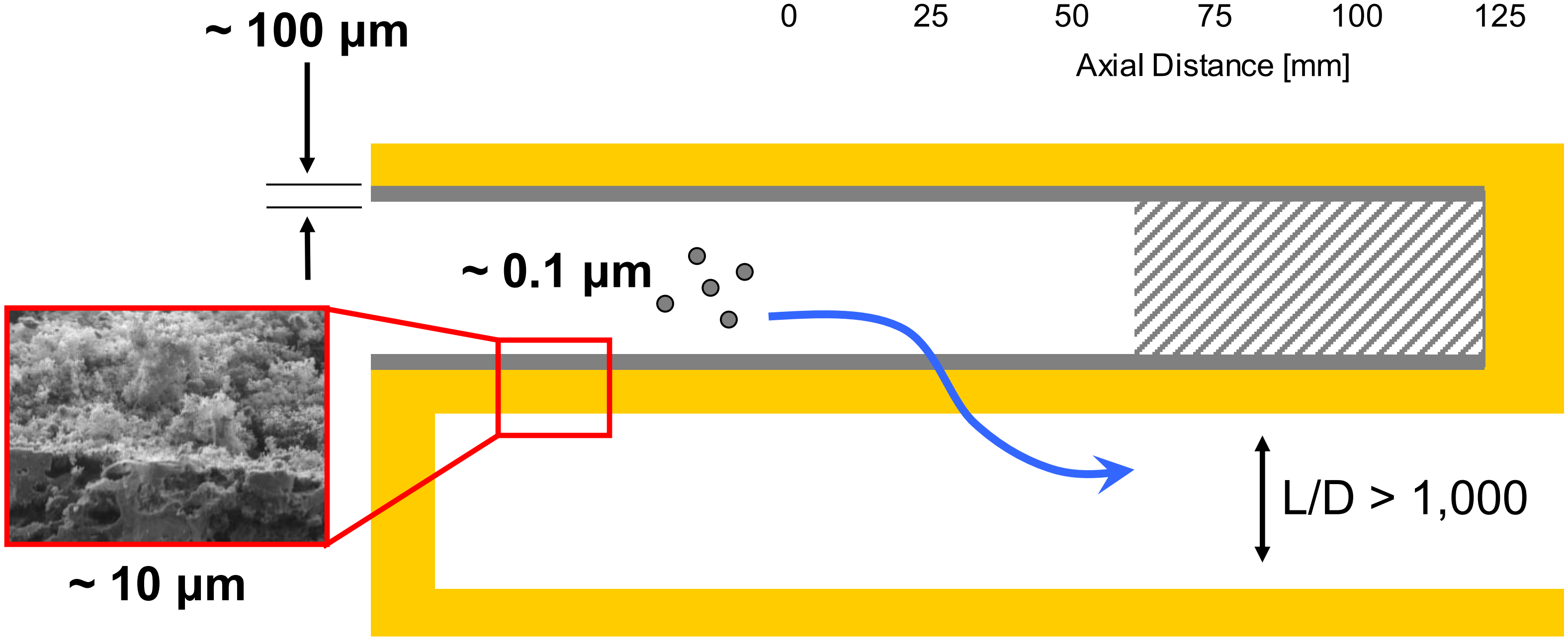
Ash Build-Up in the DPF is a Dynamic Process

Ash Accumulation

- **60%** of ash layer thickness from first **30%** of ash deposits
- Ash preferentially accumulates in end-plugs during later stages of ash build-up

Ash First Deposits Along Channel Walls





Lubricant Additive Tracers Track Ash Distribution

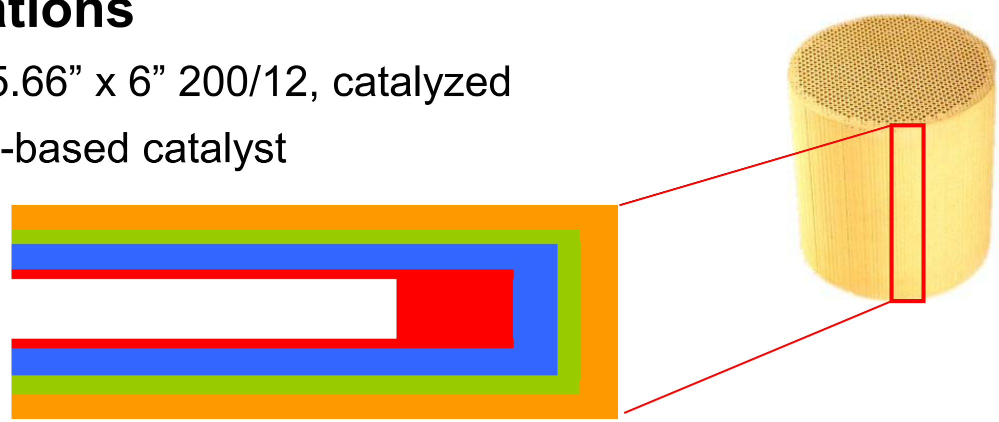
Additive Tracers

- All oils formulated to 1% sulfated ash
- Applied in series to same DPF (~ 7 kg of oil each)

Elemental Composition [wt. %]							
Order of Application		Ca	Mg	Zn	S	P	Total
1	Base + Ca	0.30			0.04		0.33
2	Base + Zn			0.36	0.69	0.33	1.37
3	Base + Mg		0.21		0.05		0.25

DPF Specifications

- Cordierite – D5.66” x 6” 200/12, catalyzed
- Washcoat + Pt-based catalyst



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

DPF Pressure Drop Evolution with Additive Tracer

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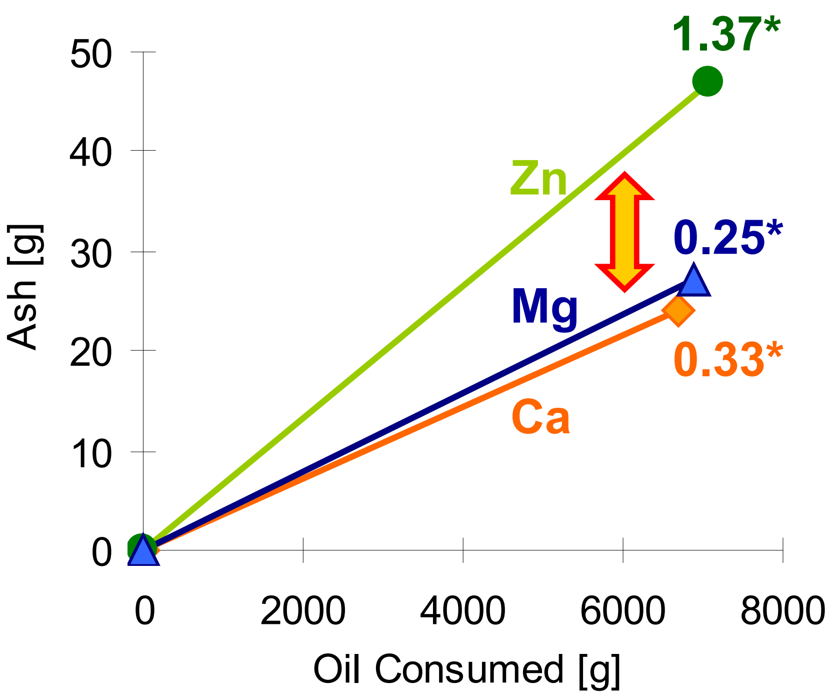
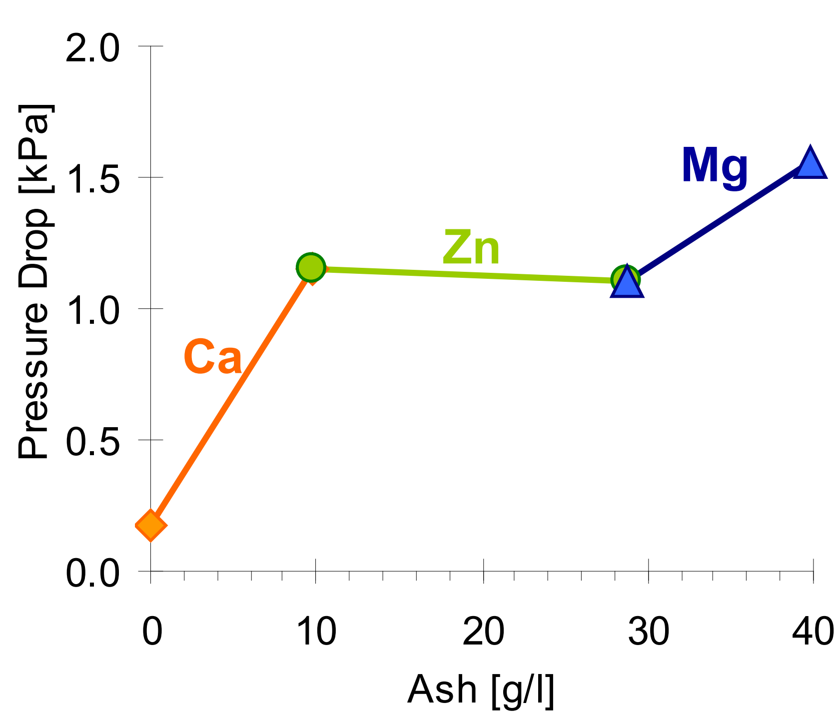
DPF Ash vs. Oil Consumed



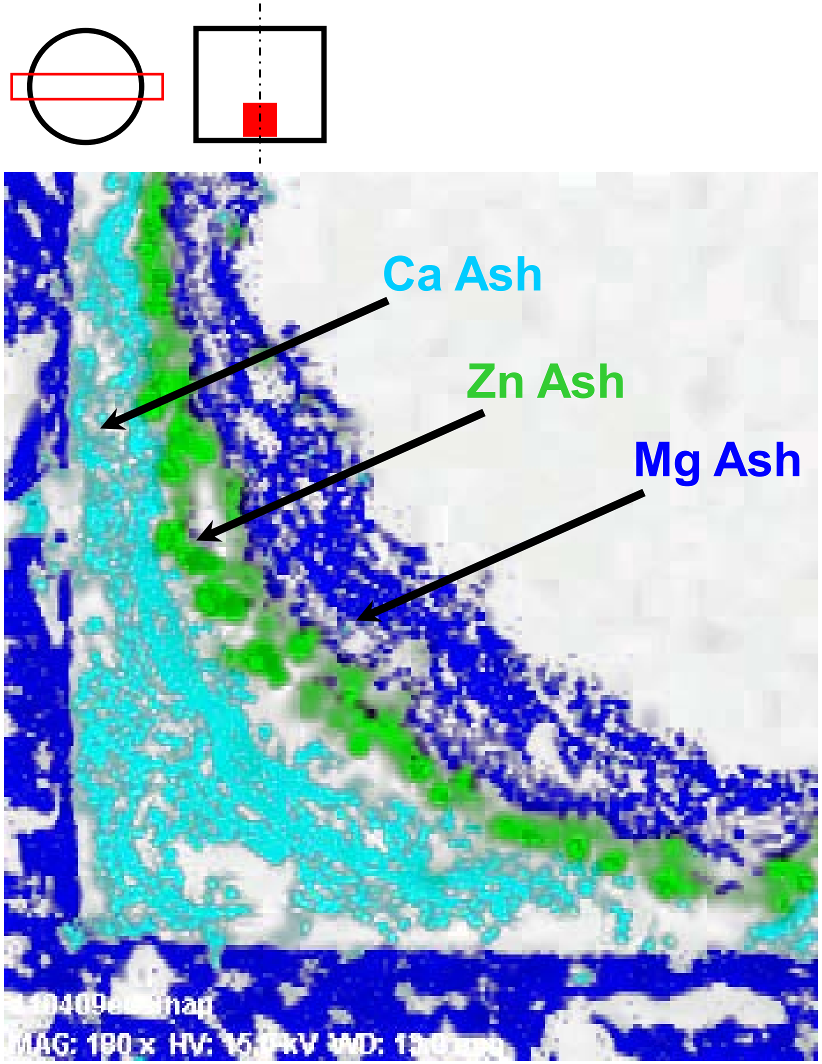
DPF Pressure Drop



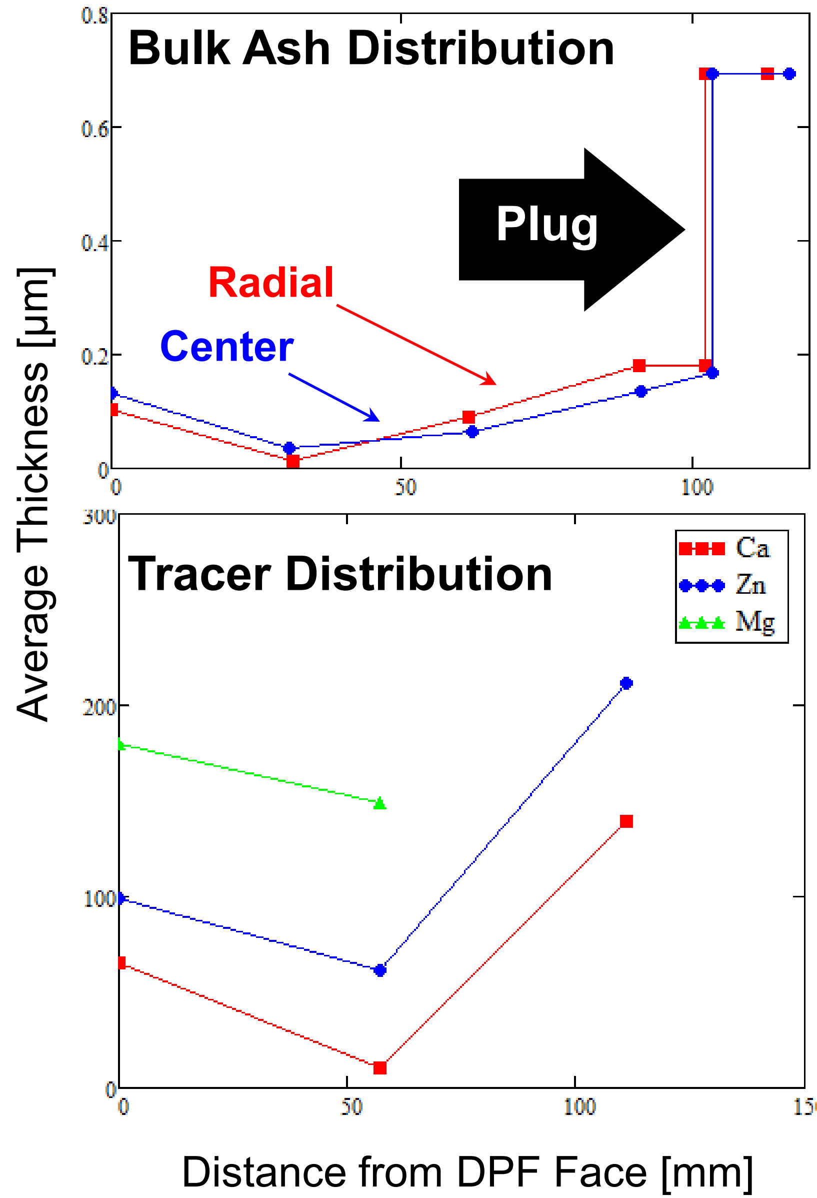
- **Nearly twice as much ash produced with base oil + ZDDP**
  - Due to greater proportion of sulfur and phosphorous content
- **Despite 2X more ZDDP ash, little increase in pressure drop**

*Total elemental ash-related additive content

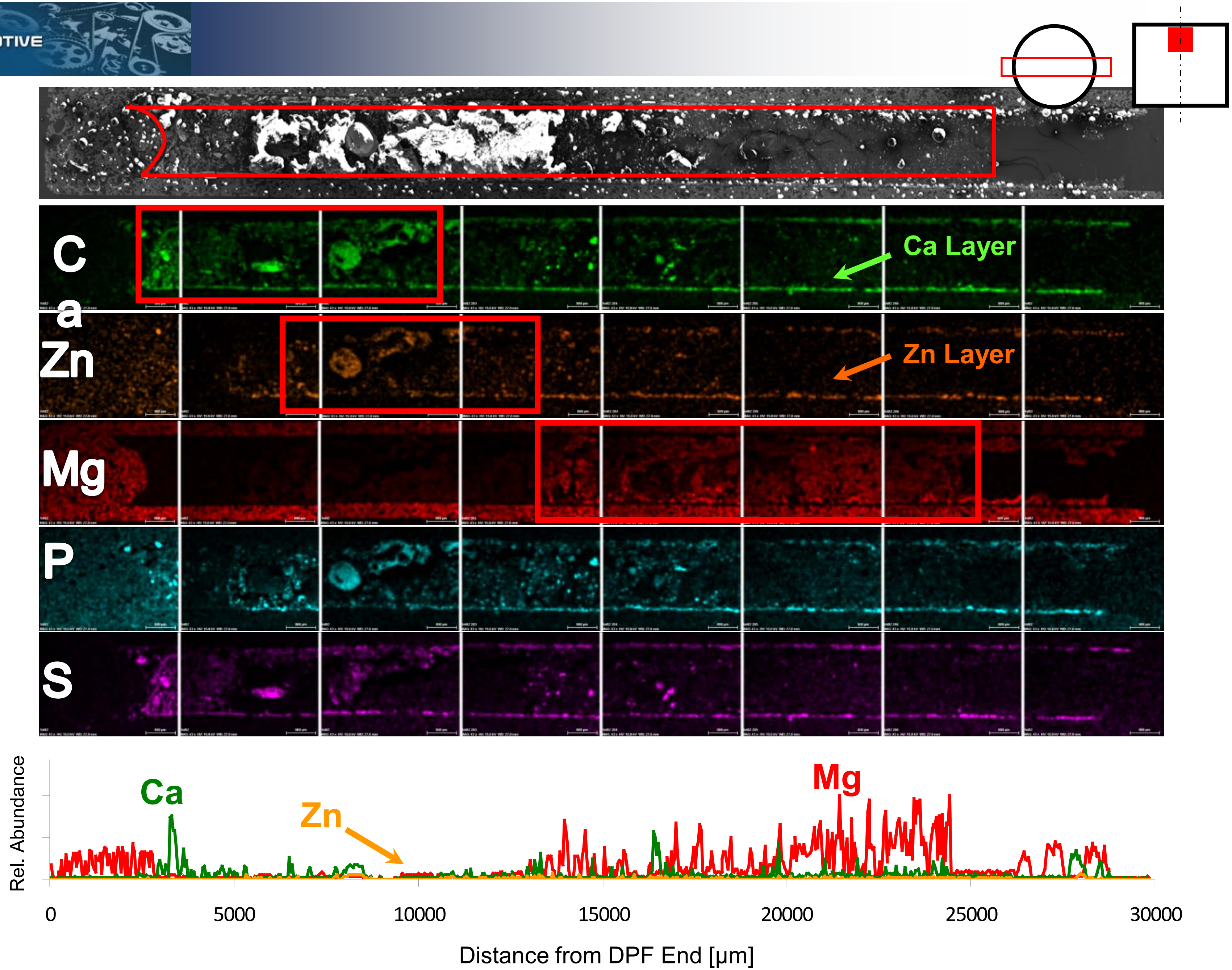
Application of Tracer Produces Stratified Ash Layers



DPF Substrate



Ash Plug Evolution Consistent with Tracers



Impact of Exhaust Conditions on Ash Properties

Exhaust Temperature Significantly Affects Ash Volume

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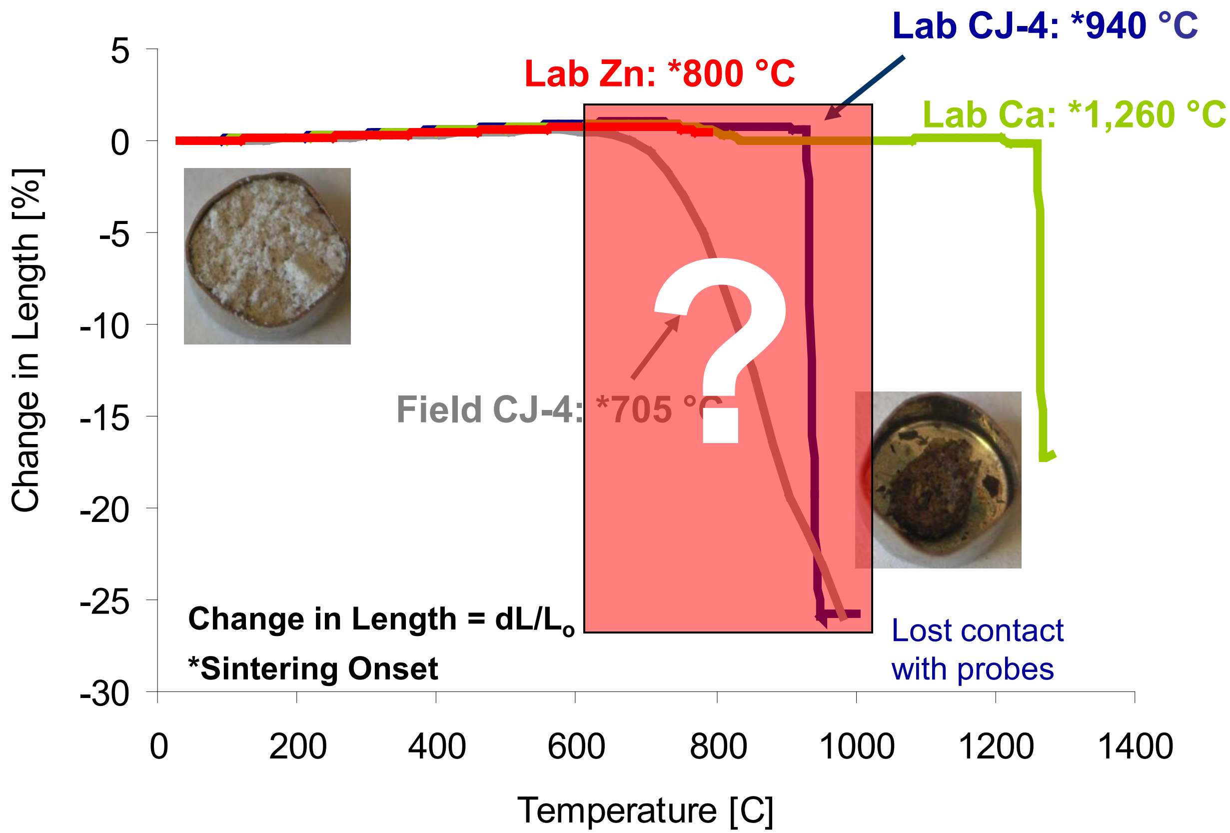
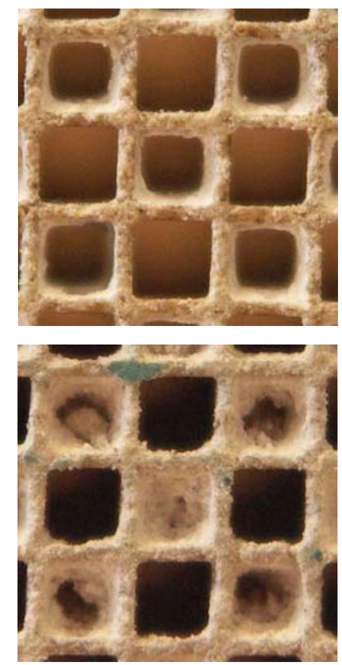


Competing Effects on ΔP Based on Ash Distribution



- **Large decrease in ash volume for temperatures over 700 °C**
  - Reduction in ash weight over temperature ranges less than 10%
  - Typical ash porosities 85% - 95% means large potential to reduce volume

MIT

Ash Core Sample Investigations of Exhaust Effects

DPF Specifications

- Cordierite D1” x 6” 200/12, catalyzed

Lubricant Composition

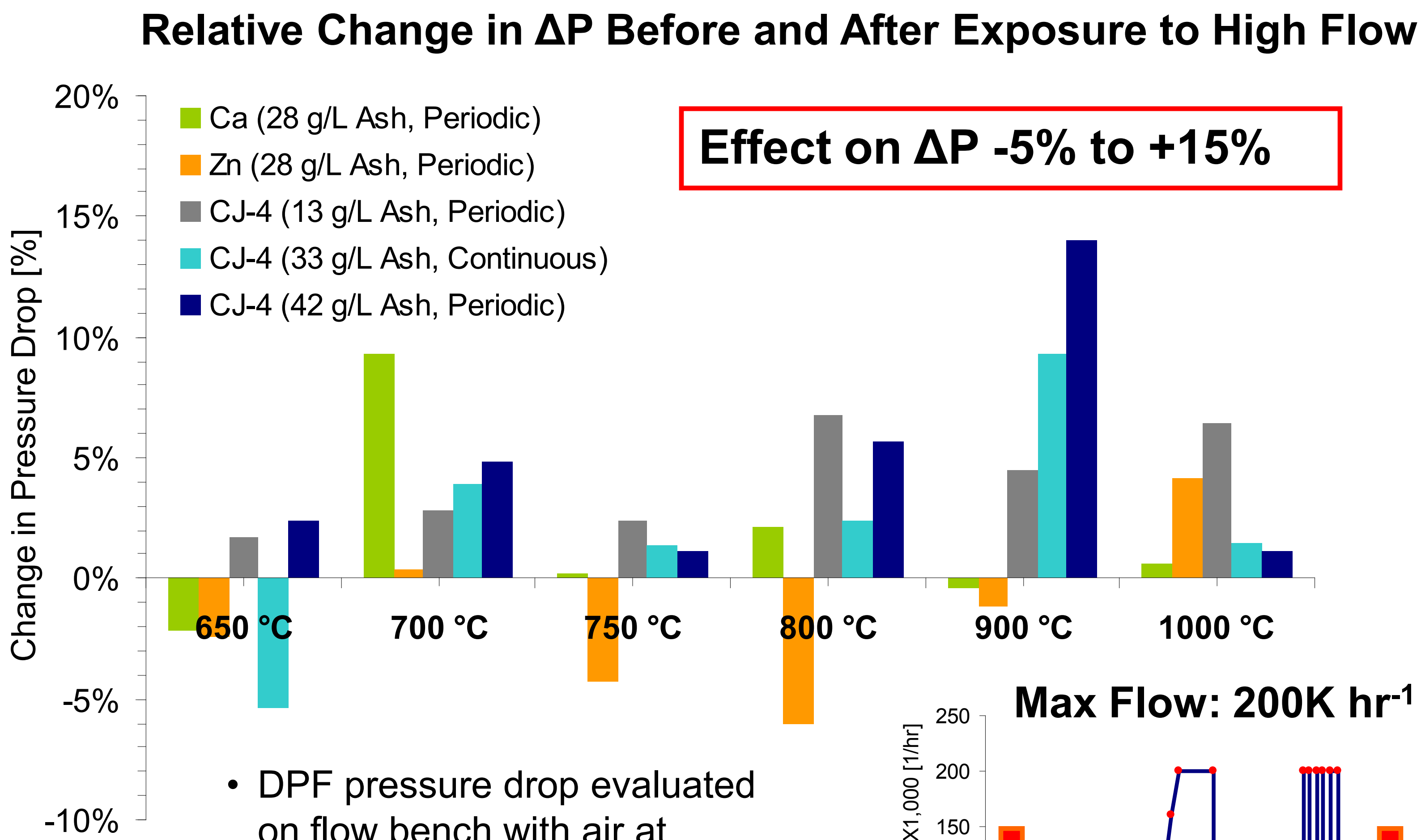
- All oils formulated to 1% sulfated ash

DPF	Ash Level	Lubricant	Regeneration
Cordierite Catalyzed 200/12	12.5	Commercial CJ-4	Periodic
	42		
	33		Continuous
	28	Base Oil + ZDDP	Periodic
	29	Base Oil + Ca	

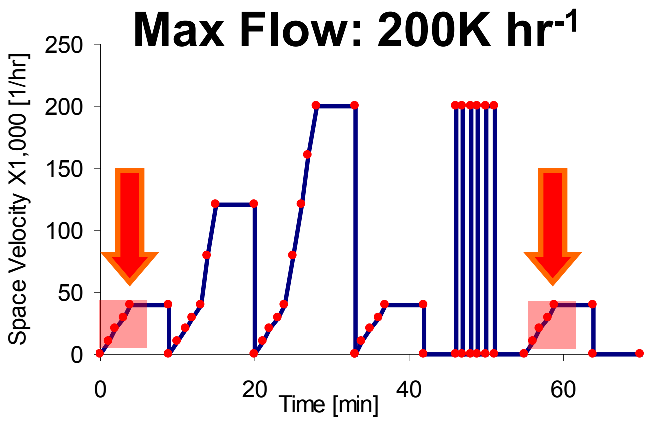
DPF Ash-Loaded Core Sample Test Procedure (Duplicate)

1. Evaluate pressure drop response using flow bench with air (ambient)
2. Heat core samples in furnace 1.5 hr (650 C…..1,100 C)
3. Re-evaluate DPF pressure drop response on flow bench (1)

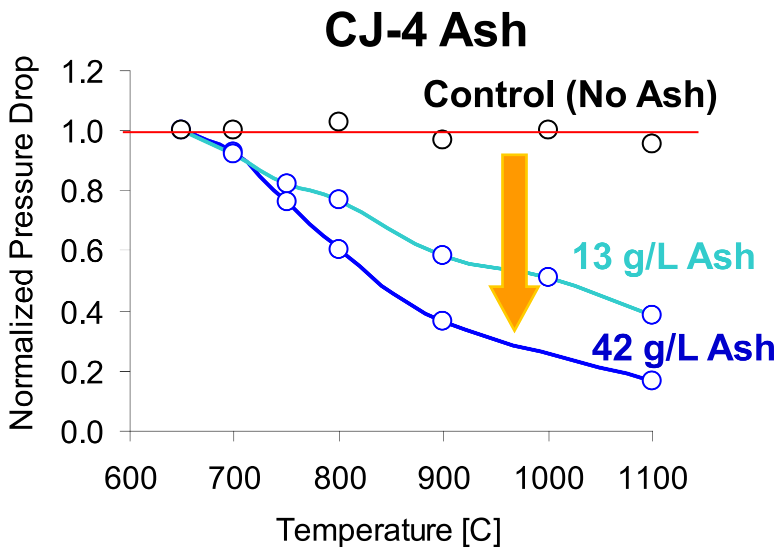
Short-Term High Flows have Small Effect on Ash Packing

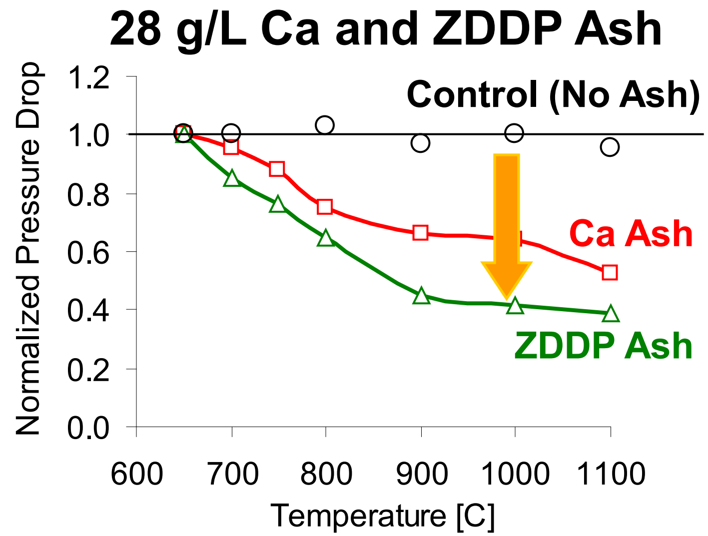


- DPF pressure drop evaluated on flow bench with air at ambient conditions
- Filters heated to specified temperature for 1.5 hours and allowed to cool prior to test

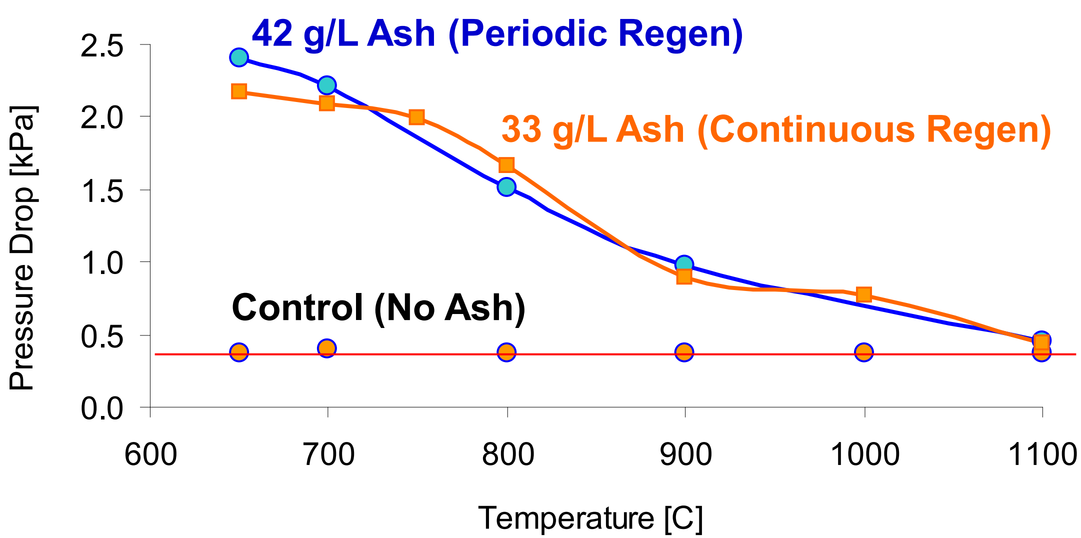


Elevated Temperatures Exert Large Effect on Ash Packing





30% - 60% Reduction in ΔP with Short-Term Exposure to 900 C

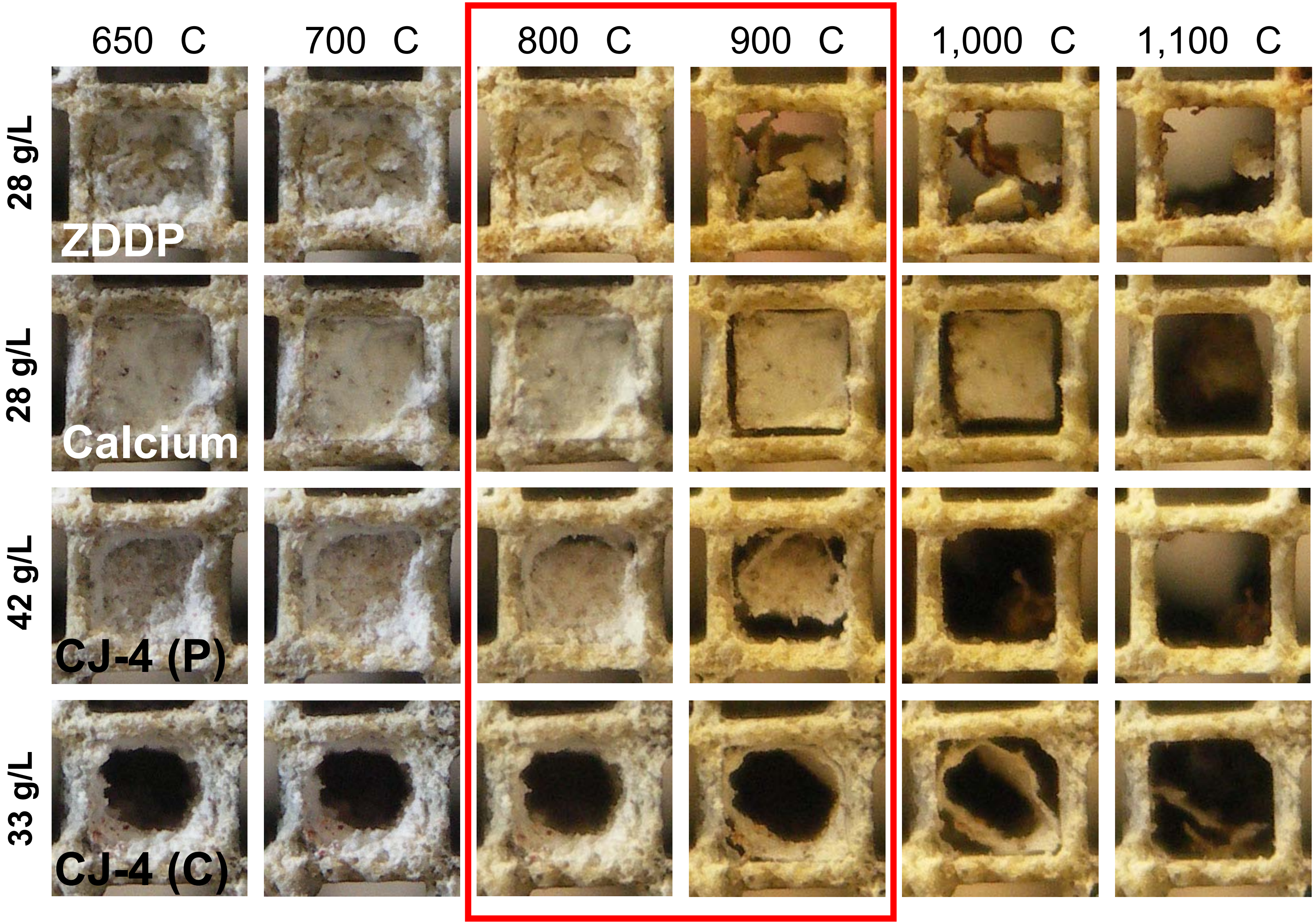


<u>Conditions</u>

Air: 25 C

SV: 50,000 hr^{-1}

Large Reduction in Ash Volume at Elevated Temperatures



High Temperatures Cause Ash Layer Cracking/Shrinking

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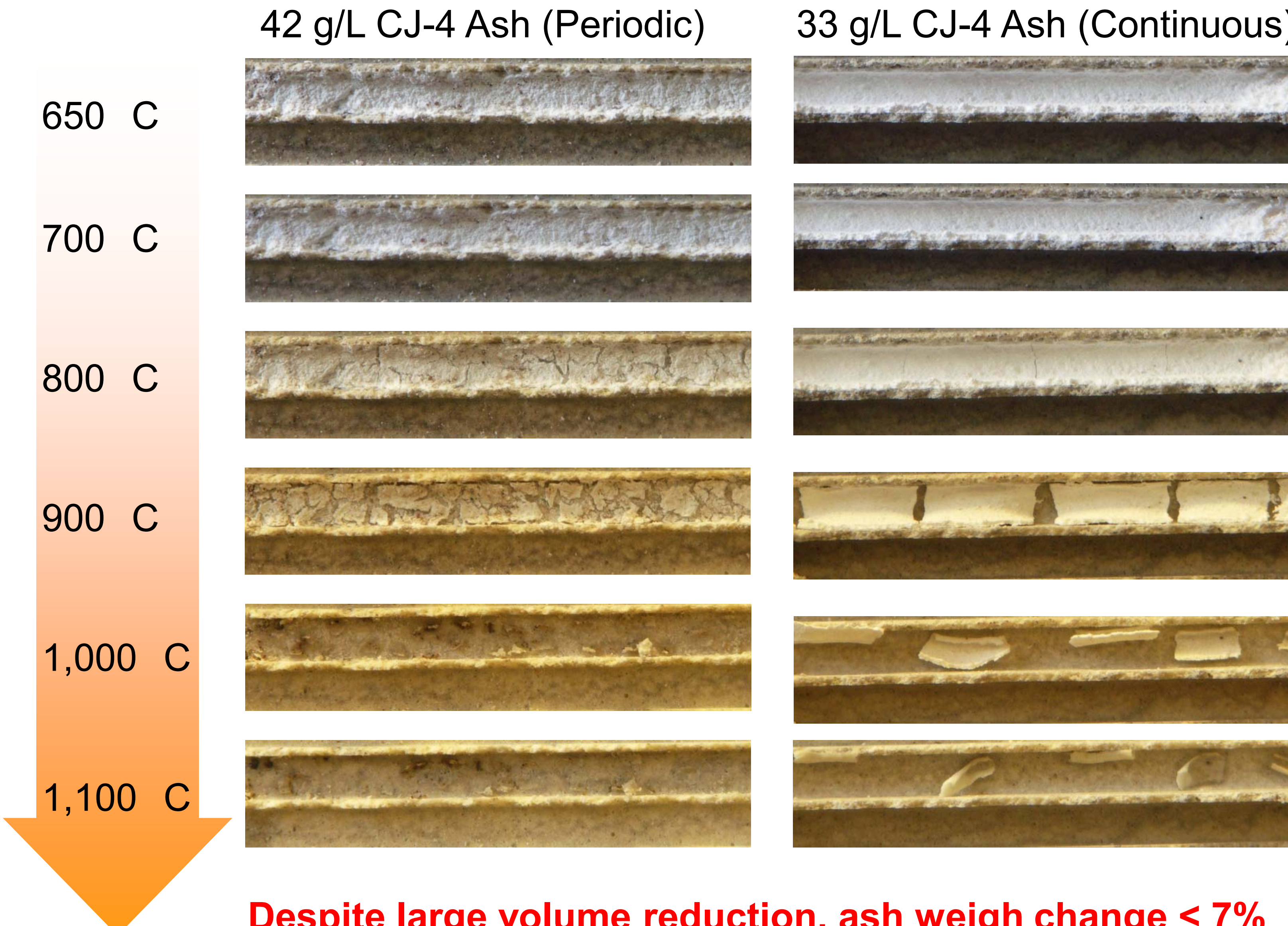

Despite large volume reduction, ash weigh change < 7%

Summary and Conclusions

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I. Ash Accumulation and Distribution

- Lubricant additive tracers applied to track evolution of ash deposits
- Increase in DPF pressure drop much greater with **Ca** and **Mg** than **ZDDP**
- Ash preferentially accumulates in plug during later stages of deposition

II. Ash Sensitivity to Exhaust Conditions

- Short-term exposure to high flow rates (200K hr^{-1}) exert little effect on ash packing and DPF pressure drop
- Elevated temperature excursions have the potential to significantly reduce ash-related pressure drop **30% - 60%**
- High porosity of ash responsible for large reduction in volume when heated
- Effects on DPF integrity and ash removal require additional investigation

Acknowledgements

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

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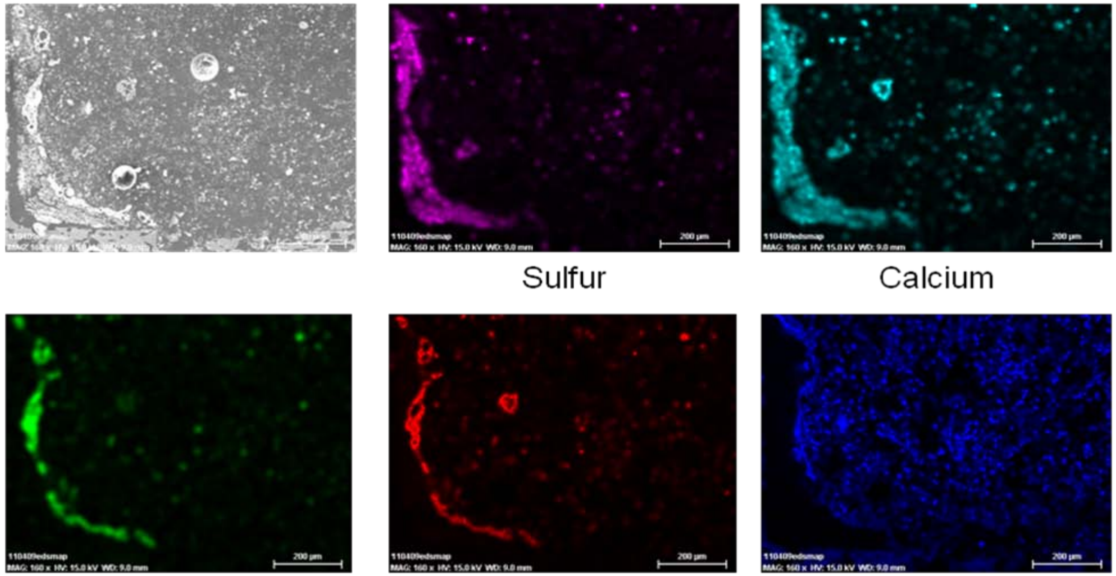
- Detroit Diesel	- Infineum	- Komatsu
- NGK	- Oak Ridge National Lab	- Süd-Chemie
- Valvoline	- *Ford*	- *Lutek*

- MIT Center for Materials Science and Engineering

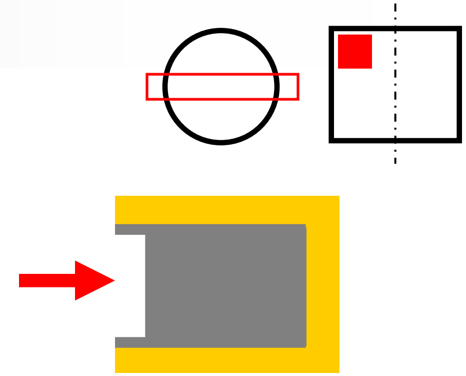
Ash Plug Formation and Build Up

Front of Plug



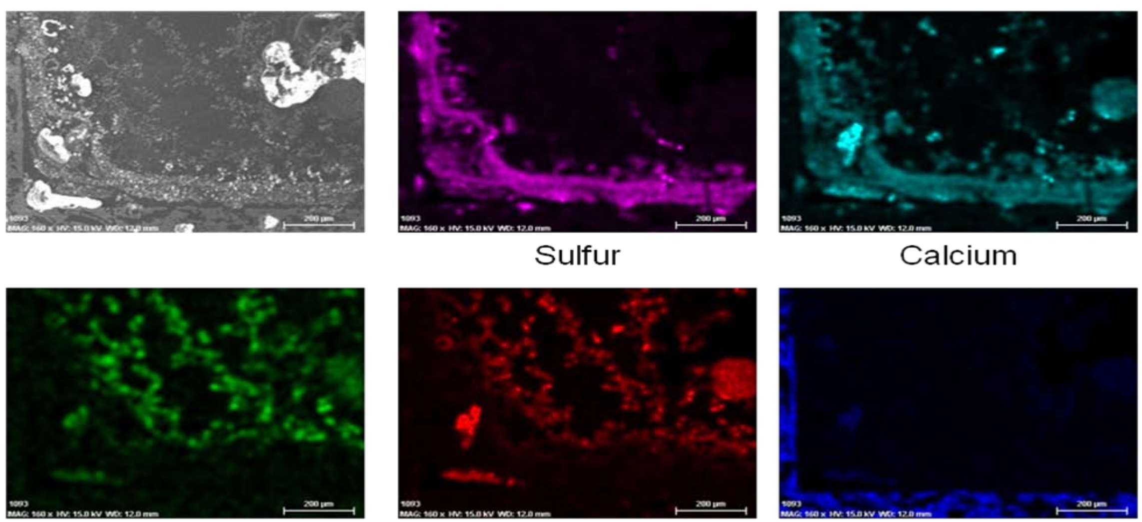
Sulfur | Calcium

Zinc | Phosphorus | Magnesium



Front of plug mostly Mg

Back of Plug



Sulfur | Calcium

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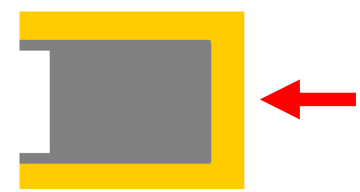

- No Mg in back of plug
- Zn and Ca dominant