CORNING

Diesel Aftertreatment Systems

Jeff Kohli
Tim Johnson

14 August 2007

11th ETH Conference on Combustion Generated Nanoparticles

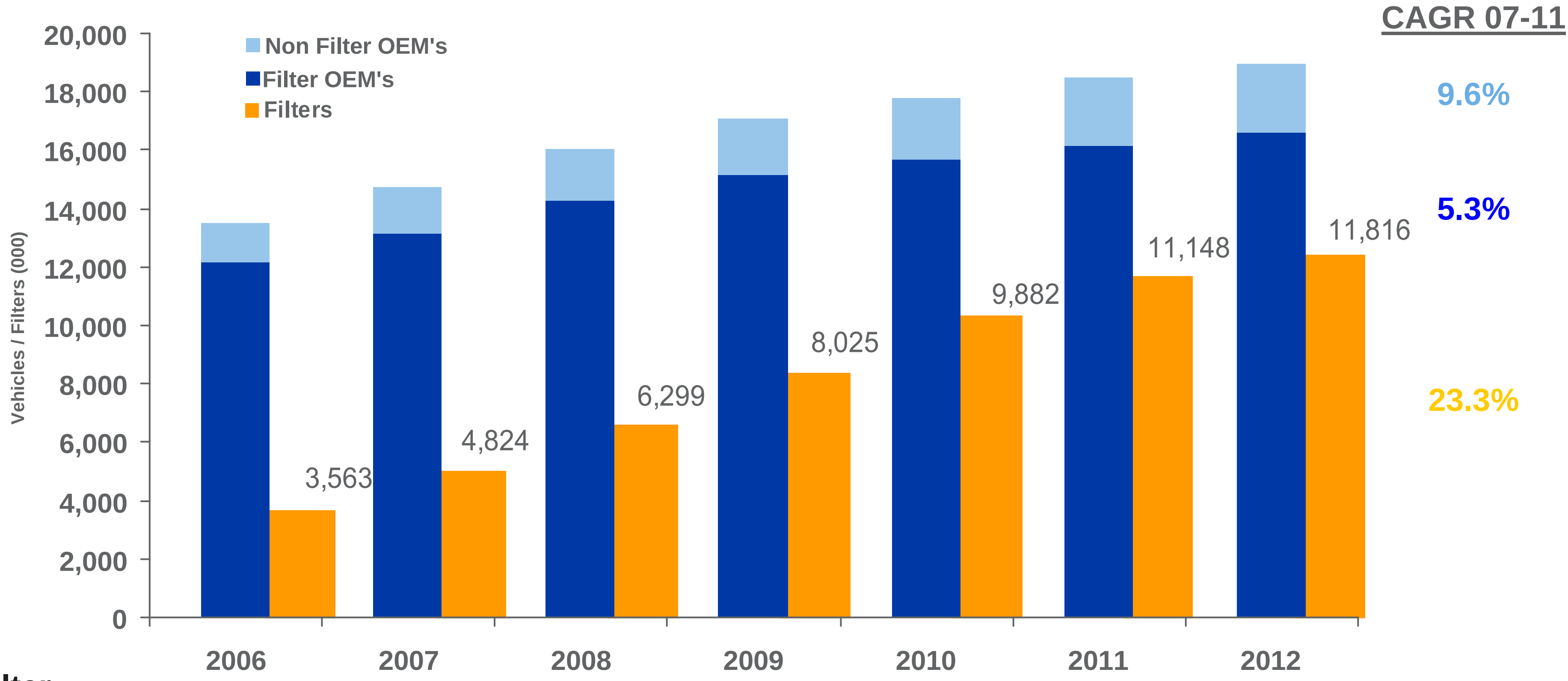
Summary and Outline

"DPFs are becoming as much a part of the modern diesel engine as direct injection and turbocharging." Ulrich Dohle, President Bosch Diesel, 2006.

- Diesel system trends described
- Sophisticated regeneration control strategies emerging
- Materials and filter design optimization in progress
  - Three major DPF materials in the market
  - Pore size effects on filtration efficiency (~ 20 µm threshold)
  - Wall attributes, cell structure, and cell density
  - Ash management
- NOx aftertreatment trends and complexity being addressed

Light-Duty Diesel

Vehicle Production & Filter Demand



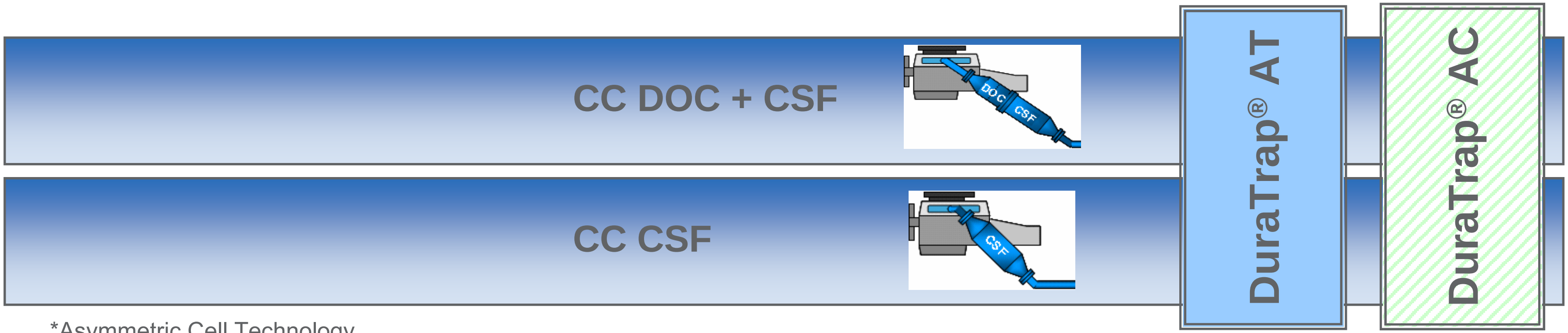
Filter Penetration	**29%**	**37%**	**44%**	**53%**	**63%**	**69%**	**71%**

Non Filter OEM's: India & China Local

Light-Duty Diesel Systems Trend

Close-Coupled Filters

- **Drivers**
  - Potential for fewer components → cost, space considerations
  - More continuous regeneration due to higher temperatures
  - Less post-injection fuel penalty and oil dilution
- **Enablers**
  - Smaller filters
    - More ash-storage capacity (→ ACT)
  - Integration of catalyst function on the filter (CSF) with optimal pressure drop performance
    - Optimized porosity & washcoat interaction



CC DOC + CSF

CC CSF

DuraTrap® AT

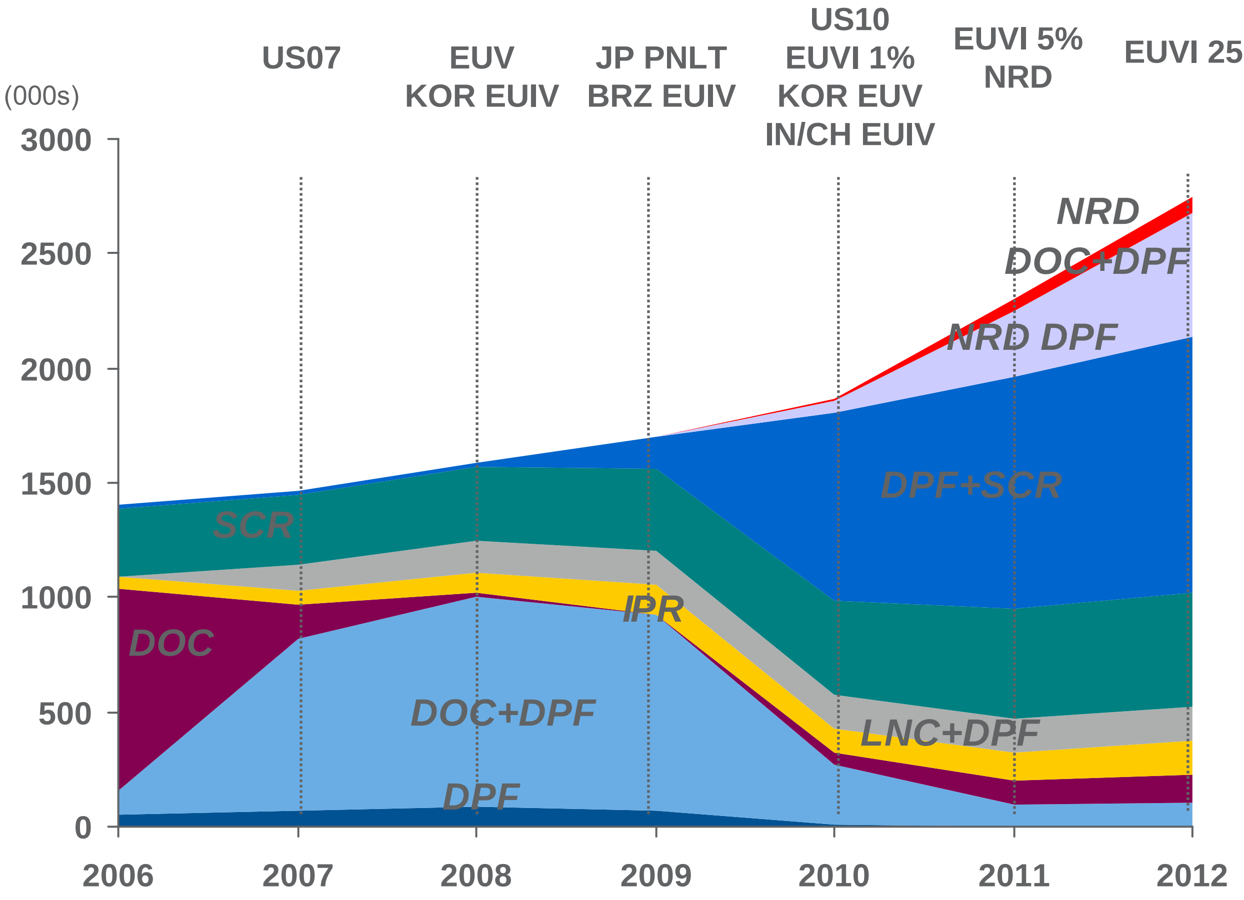
DuraTrap® AC

*Asymmetric Cell Technology

Summary of LDD Trends for PM and NOx Aftertreatment

- Clear majority of systems include a DOC with the DPF
- Two major architectures are emerging
  - Close-coupled filter
    - AT and SiC optimized for higher SML applications
    - Cordierite applicable with proper controls
  - Under-floor filter with secondary fuel injector or vaporizer
    - Allows long oil-change intervals (oil dilution addressed)
- Interest in combining functionality is strong, but modular systems are the norm for the near term
  - DOC + DPF + LNT/SCR (as needed)

Global OEM System Forecast: On-road & Non-road



Key Assumptions

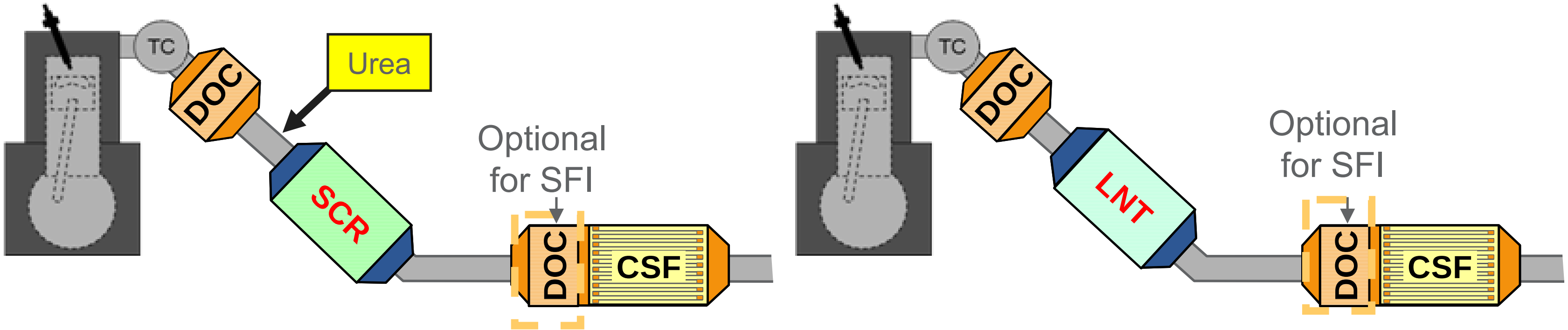
- EUVI timing: ’12-13 w/ some pull ahead
- US10/EUVI systems
  - LHD Chassis: SCR + DPF
  - LHD Engine: DPF + SCR
  - M/HHD: DPF + SCR
- Brazil: SCR and DOC+DPF
- China: SCR
- India: IPR and SCR
- 75-750 HP Non-road: DOC+DPF

Growth of filter systems continues with tightening global HDD regulations

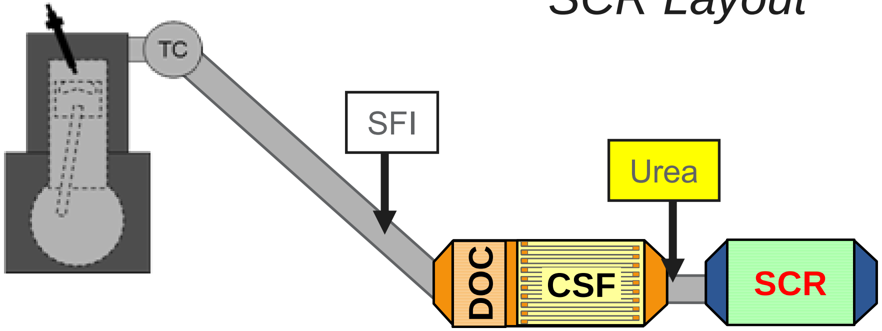
Source: Corning Forecast

Potential System Configurations for Future L-HD, MD and HD On-road Legislation (US2010 and EUVI)

Most common L-HD Layout



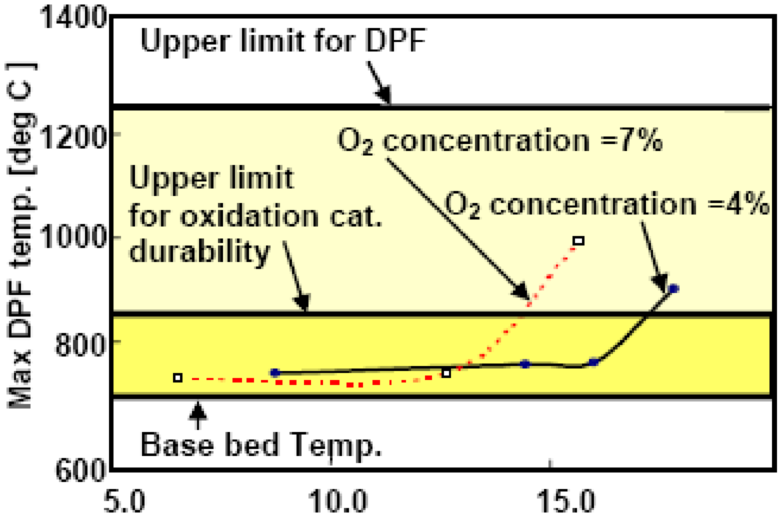
Most common HD and MD SCR Layout



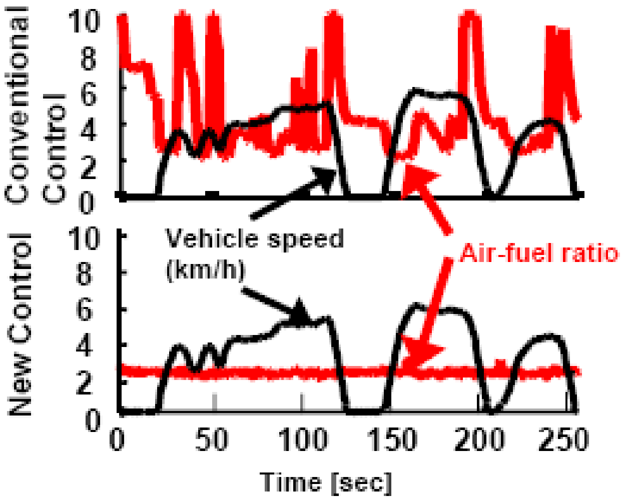
Trends:

- Typical soot loads 3-5g/l
- Some applications might require higher soot loads

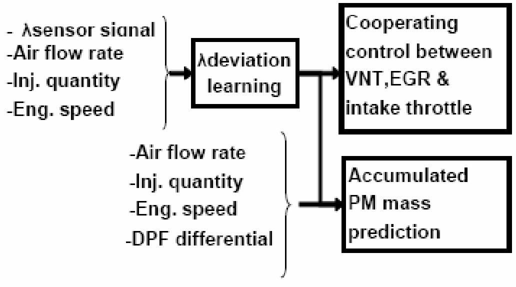
Sophisticated Regeneration Control Strategies

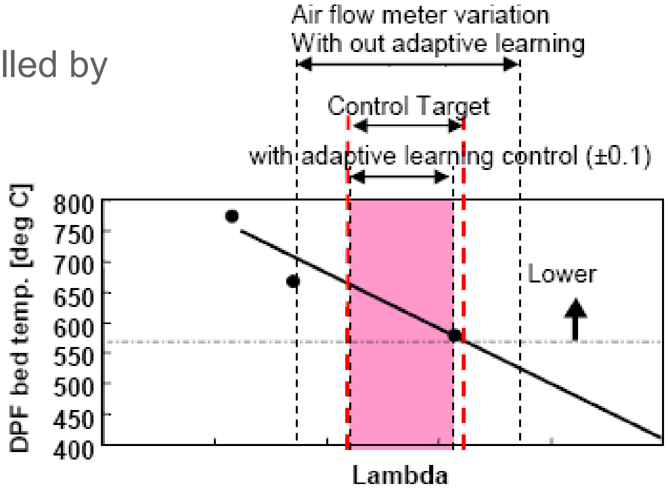


DPF bed temperature is controlled by oxygen level.



Oxygen control is very good in transient conditions.





Nissan SAE 2007-01-1061

Adaptive learning tightens A/F control and allows better soot estimation.

Key Properties of Diesel Particulate Filter Materials

Property	**DuraTrap® AC**	**DuraTrap® AT**	**SiC**
Material (assuming ~ 50% porosity)	Cordierite	Stabilized Aluminum Titanate	Silicon Carbide
Structure	Monolith	Monolith	Segmented
Coefficient of Thermal Expansion ($x10^{-7}/^{o}C$) ($22-1000^{o}C$)	<6	<9	~ 45
Thermal Conductivity @ 500 ^{o}C (W/mK)	~1.0	~1.0	10-20*
Specific Heat Capacity @ 500 ^{o}C ($J/cm^{3}\,^{o}C$)	2.79	3.60	3.63
Thermal Shock Parameter (^{o}C) [a]	>800	>900	<300
Strain to Failure (%) (bending strength/elastic modulus)	~0.05	~0.10	~0.05
Allowable Thermal Gradient	high	very high	low

a: MOR/(E_{mod} x CTE)

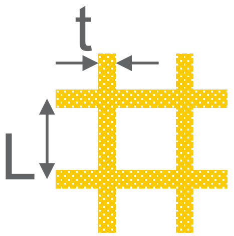
* Dependent upon bonding type

General Material and Design Interactions

Influencing Parameters	**Strength**	**Bulk Heat Capacity**	**Soot Mass Limit**	**Pressure Drop**	**Filtration Efficiency**	**Catalyst Storage Space**
% Porosity (constant cell density & wall thickness) ↑	↓	↓	↓	↓	↓	↑

- Bulk density, $\rho^{bulk} = \rho^{material} \times \underbrace{(1\text{-}P)\,(1\text{-}OFA)}_{\textbf{amount of ceramic material}}$

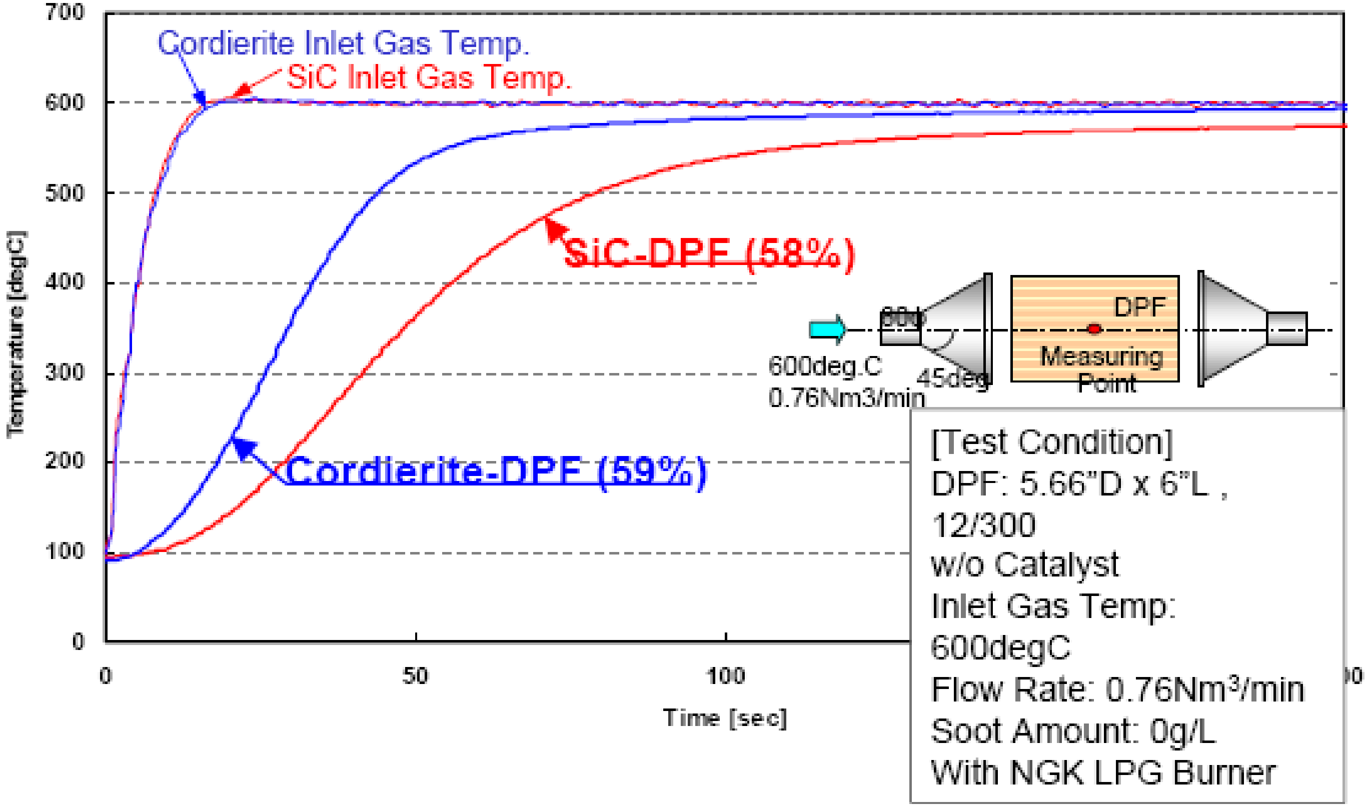
- Bulk heat capacity, $c_p^{bulk} = c_p^{material} \times \rho^{bulk}$



	200/12		300/15	
Wall Porosity	50%	60%	50%	60%
Bulk Density - Matrix	394 g/l	315 g/l	590 g/l	470 g/l
OFA - Total	68.5%		53.0%	
OFA - Inlet Channels	34.3%		26.4%	

ρ = density, P = wall porosity, c_p = heat capacity, OFA = open frontal area = $(L\text{-}T)^2/L^2$

Cordierite DPF reaches soot burning temperatures in about half the time of SiC. Attributed to lower thermal conductivity.

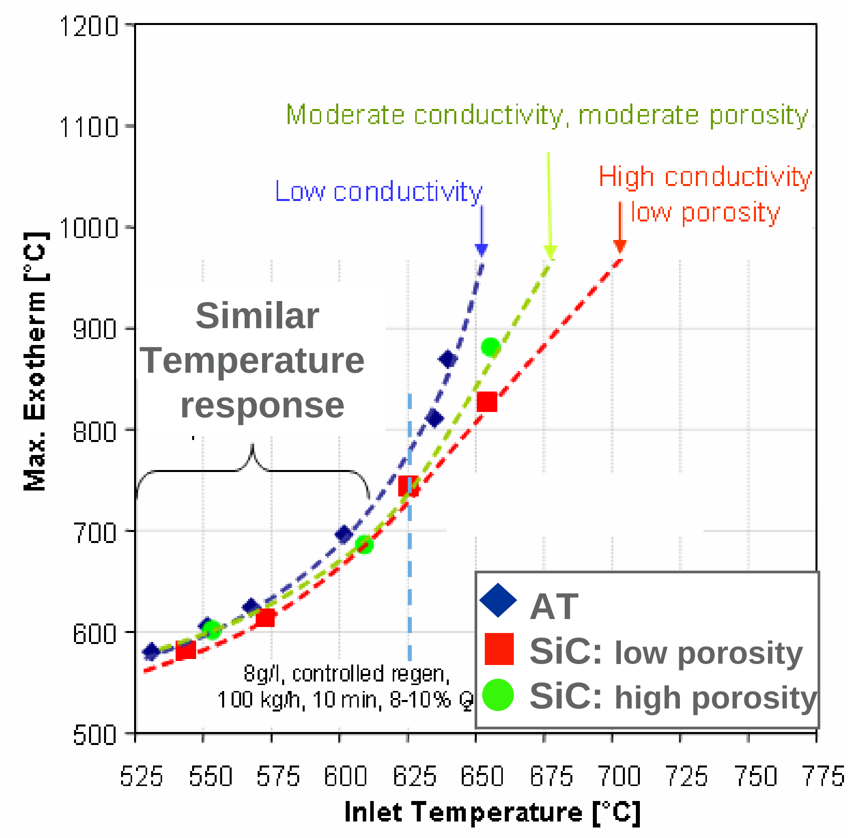


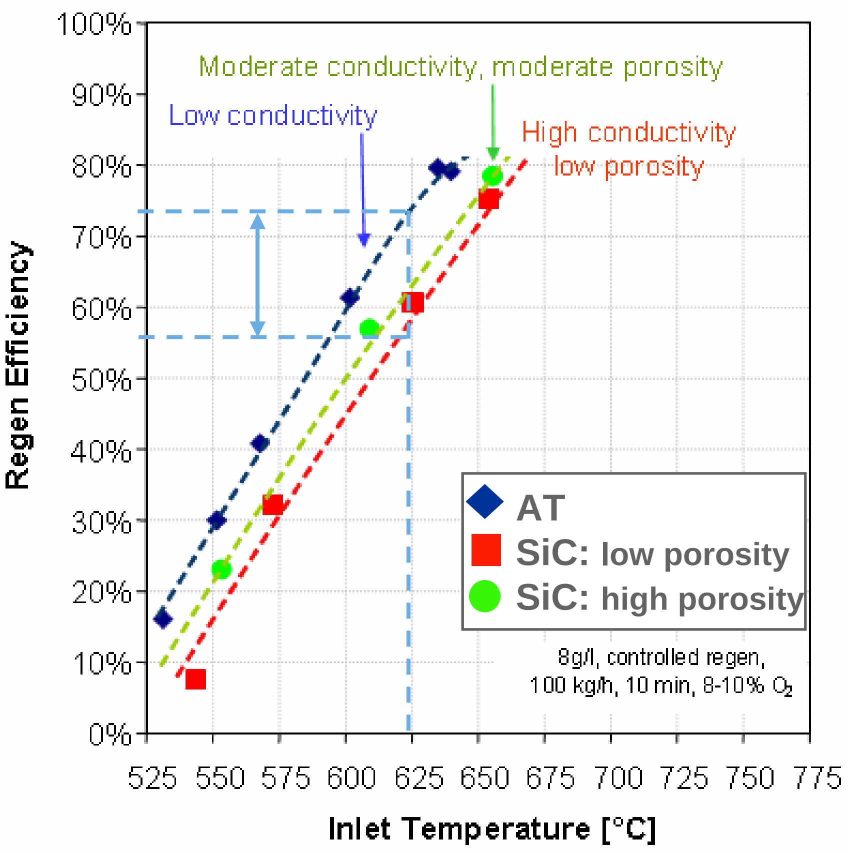
[Test Condition]
DPF: 5.66"D x 6"L , 12/300
w/o Catalyst
Inlet Gas Temp: 600degC
Flow Rate: 0.76Nm^3/min
Soot Amount: 0g/L
With NGK LPG Burner

NGK Euro V&VI Conf. 6-06

Material Properties Impact Regeneration Conditions

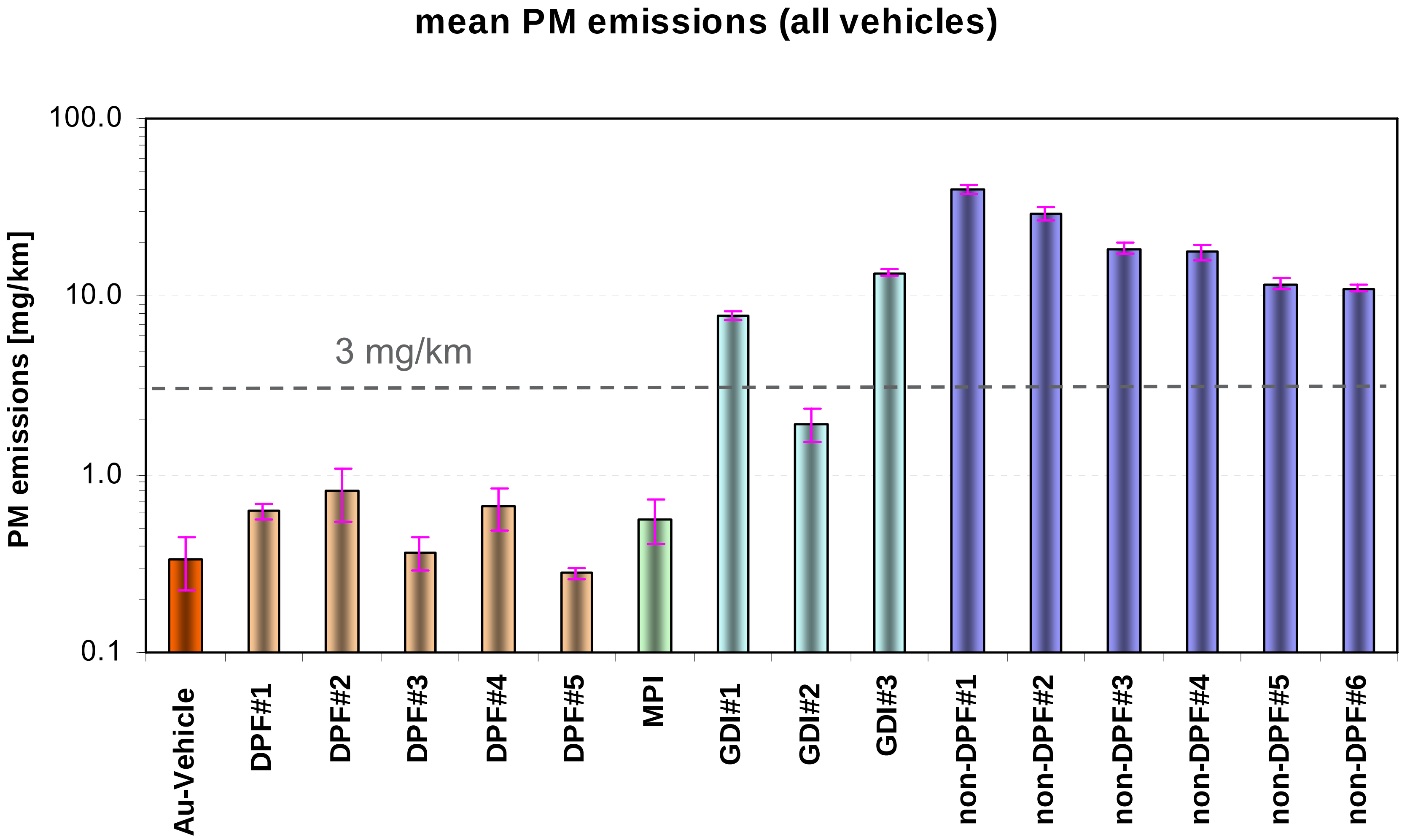
Modified Regeneration Conditions are Desired for Lower Conductivity Materials





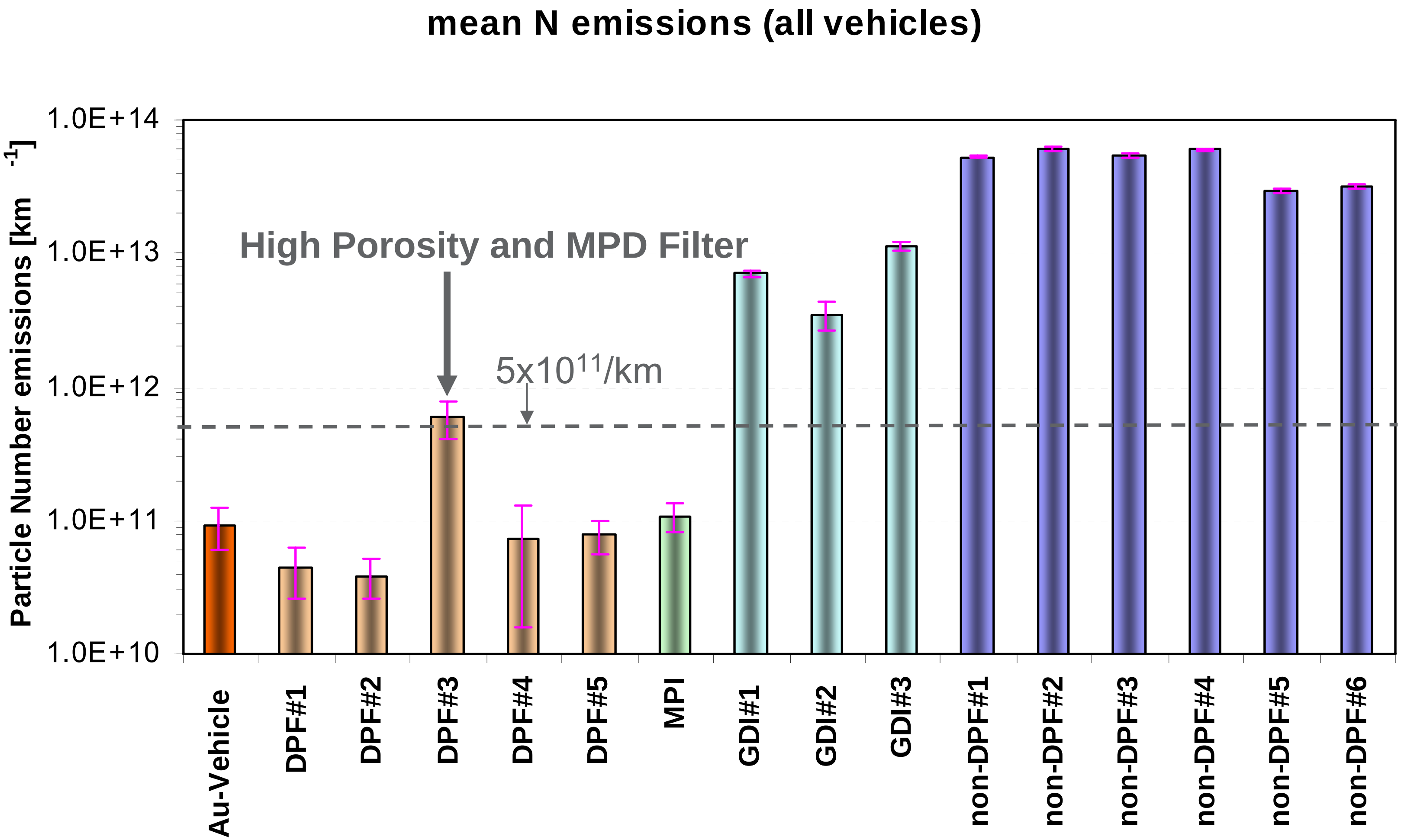
- Oxides exhibit higher regeneration efficiencies at the same inlet temperatures.
- For oxides (low thermal conductivity), slightly lower filter inlet temperatures are desirable to initiate regeneration (higher safety & lower fuel penalty to regenerate).

PMP: Mass-Based Measurements



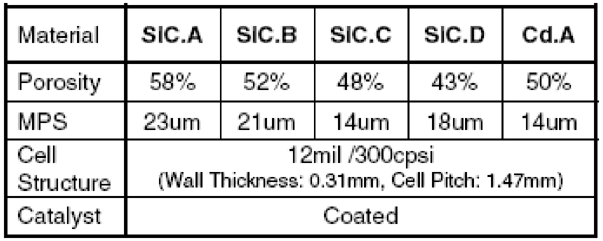
Jon Andersson et al., PMP LD Interlab. Final Report January ‘07

PMP: Number-based Measurements

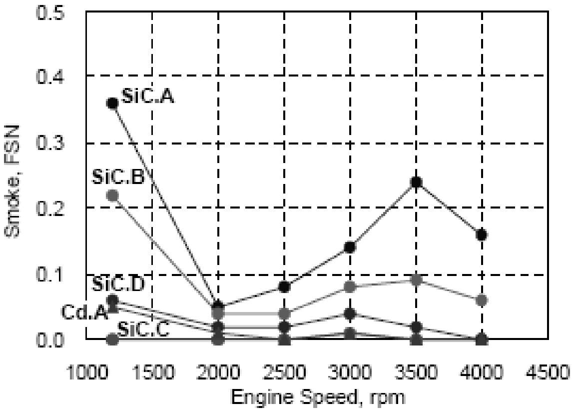


Jon Andersson et al., PMP LD Interlab. Final Report January ‘07

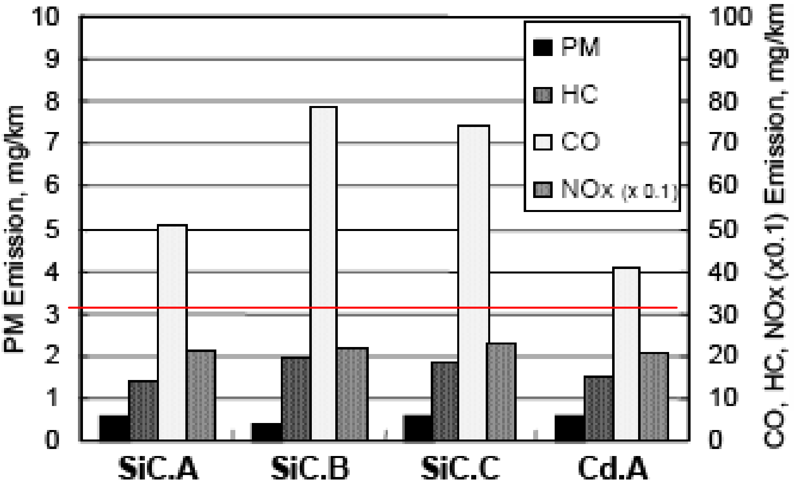
Filtration efficiency drops significantly if DPF has significant number of pores >20 µm. Balancing porosity and catalyst loading is important for optimum performance.



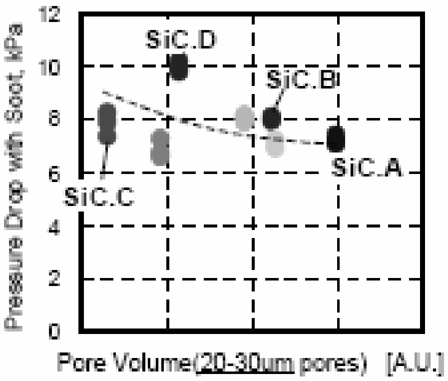
Material	SiC.A	SiC.B	SiC.C	SiC.D	Cd.A
Porosity	58%	52%	48%	43%	50%
MPS	23um	21um	14um	18um	14um
Cell Structure	12mil /300cpsi (Wall Thickness: 0.31mm, Cell Pitch: 1.47mm)				
Catalyst	Coated				



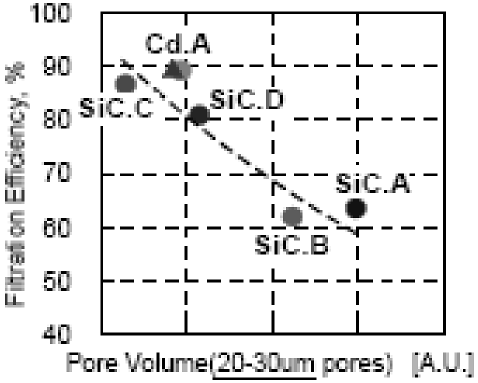
DPF with pores larger than 18 µm show much higher full load smoke numbers. Thermal properties of the filter affect soot cake regeneration properties, giving different efficiencies vs. RPM.



All filters meet the Euro 5 PM requirements (3 mg/km) on the NEDC test cycle.



Pressure drop at 4 g/l soot loading is not improved with larger pores, but is more affected by total porosity.

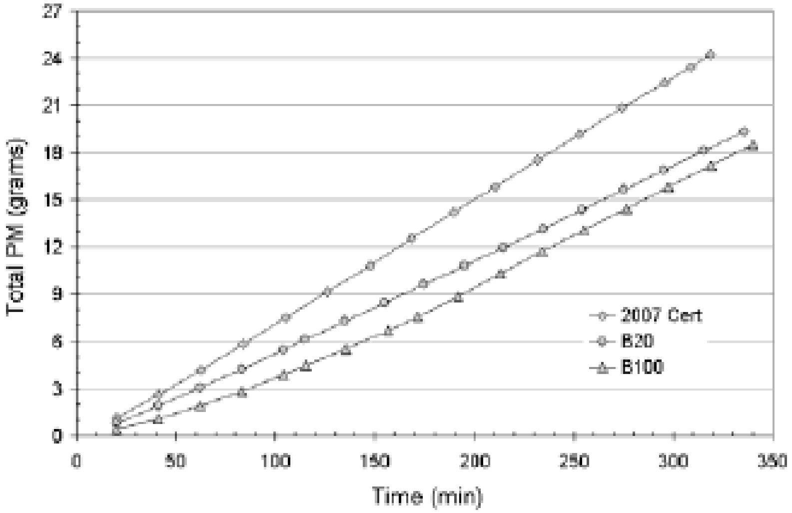


Initial filtration efficiency drops for DPFs with pores >20 µm.

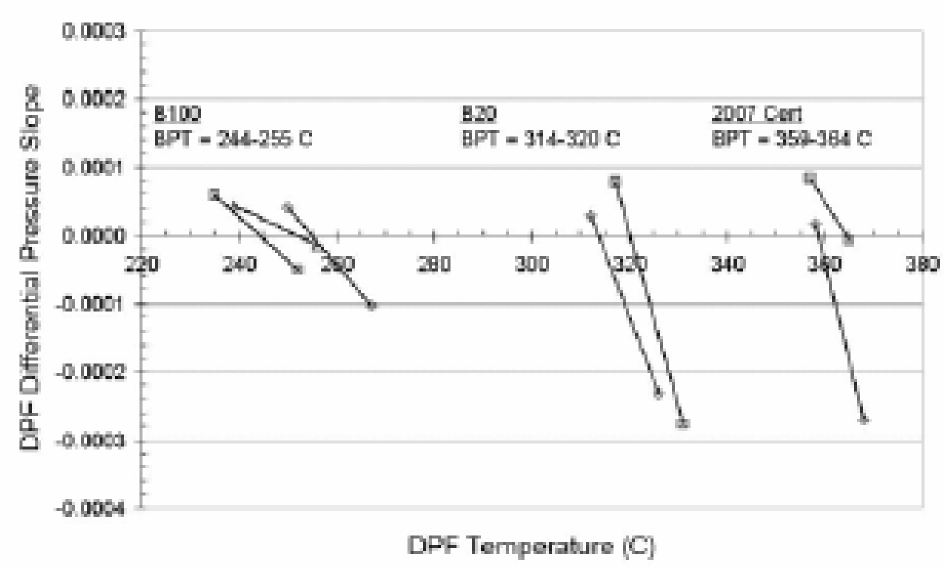
NGK, SAE 2007-01-0923

Soybean biodiesel blends produce less soot, drop balance point temperature, and result in faster burn rate.

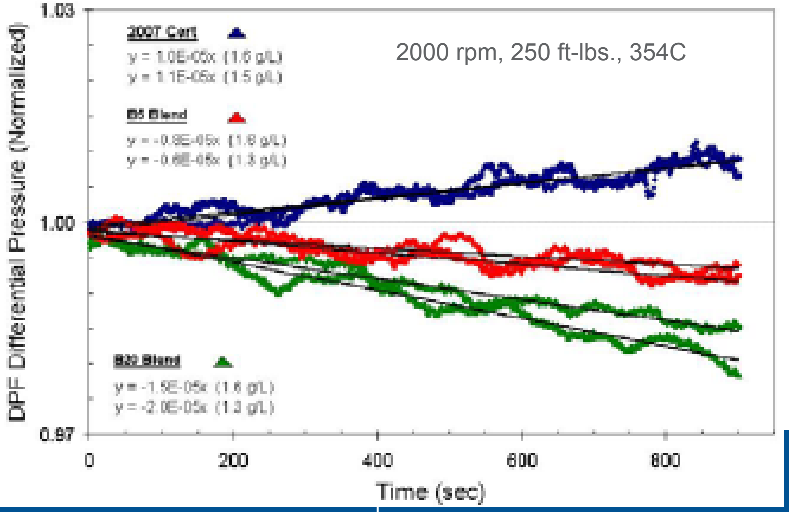
NREL, Cummins SAE 2006-01-3280



Diesel PM production rates using diesel, B20 and B100 fuel at 2000 rpm and 20 ft-lbs. torque. Cummins 5.9 liter ISB engine, MY2002.

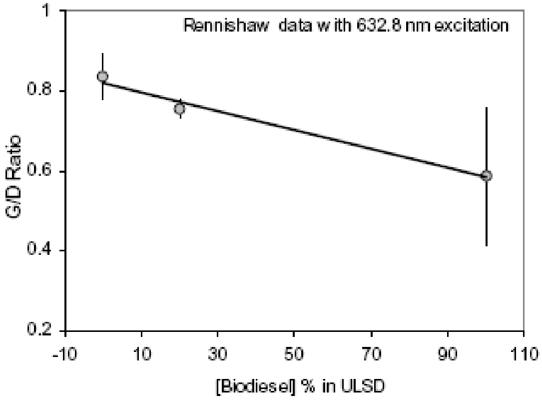


Balance point temperature results at 1700 rpm.

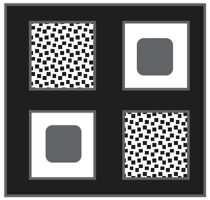


Fuel	OC µg/cm^2	EC µg/cm^2	OC/EC
2007 Cert	206.37	38.11	5.42
2007 Cert	219.07	31.79	6.89
B20	419.94	17.63	23.82
B100	414.54	15.25	27.19

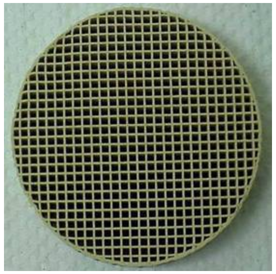
Soot combustion temperature is 550-580C for biodiesel blends, and 650-680C for diesel fuel. Difference is due to carbon structure.

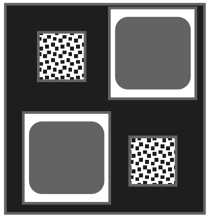


Asymmetric cell design results in lower lifetime backpressure

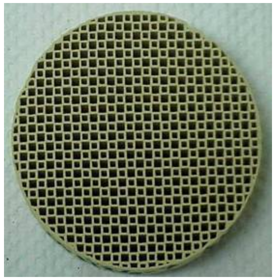


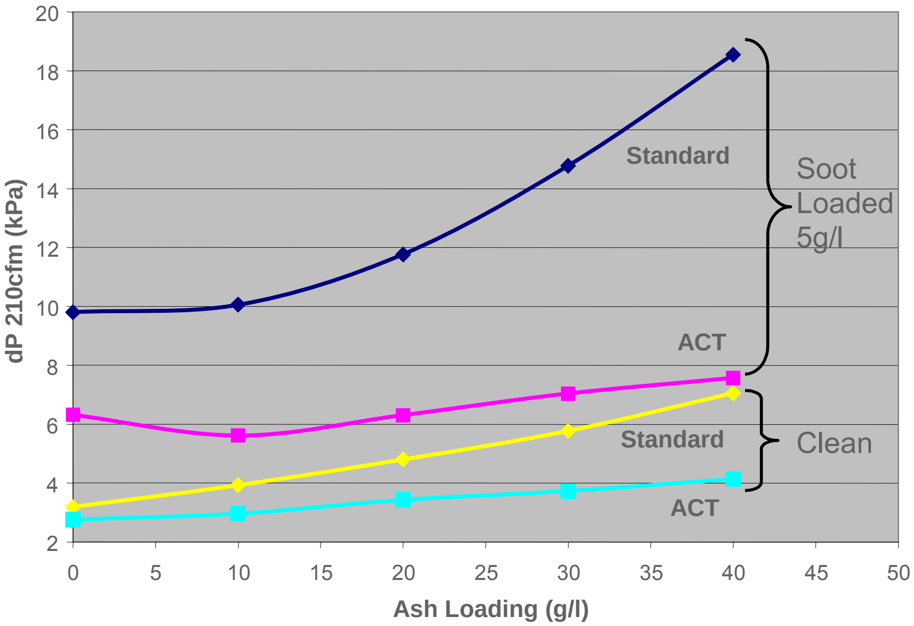
Symmetric





Asymmetric

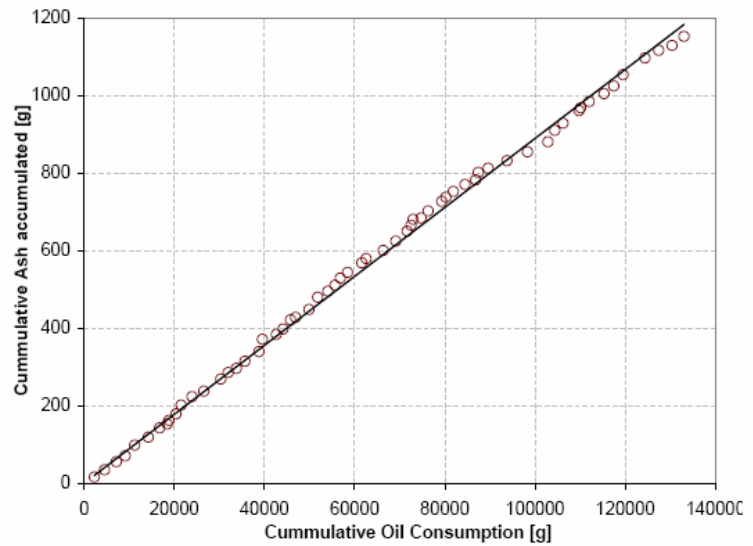




Source: Corning

DPF ash accumulation tracks lube oil consumption. Some ash goes back to the sump.

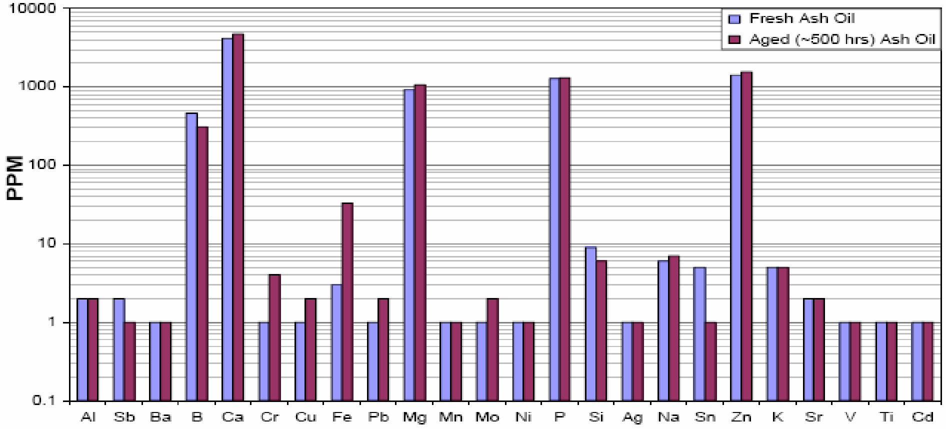
Corning, DEER 8/06



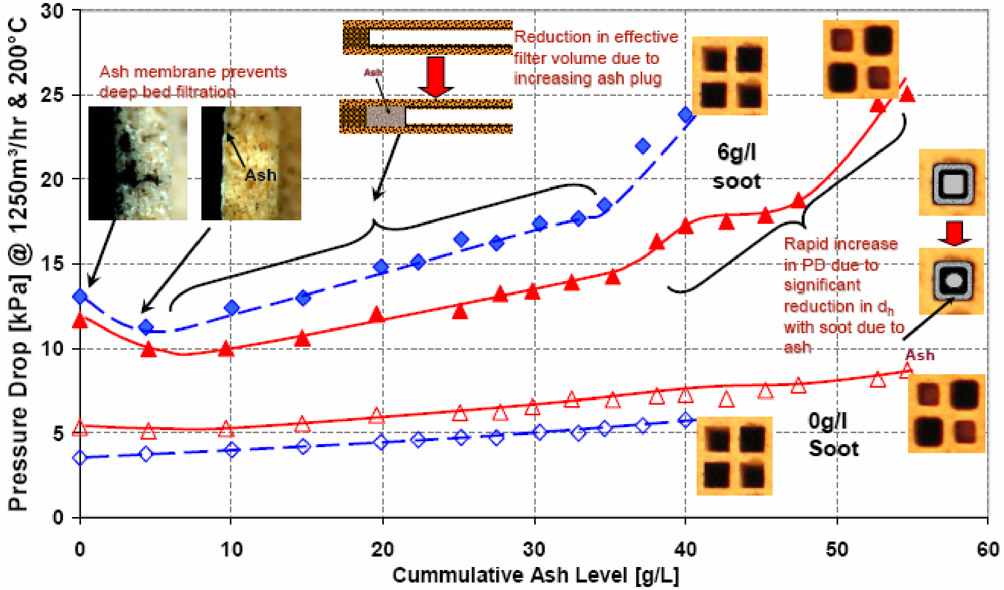
Ash accumulated on the DPF tracks lube oil consumption quite well. Only 50-56% of the total ash in the consumed oil ends up on the DPF.

Back pressure – ash accumulation behavior is explained. With soot, early ash accumulation prevents deep bed filtration, which increases back pressure. Then, loss of filtration area by ash causes pressure increase. Later, loss of hydraulic diameter causes rapid increase. Asymmetric cell geometry gives +30% ash capacity.

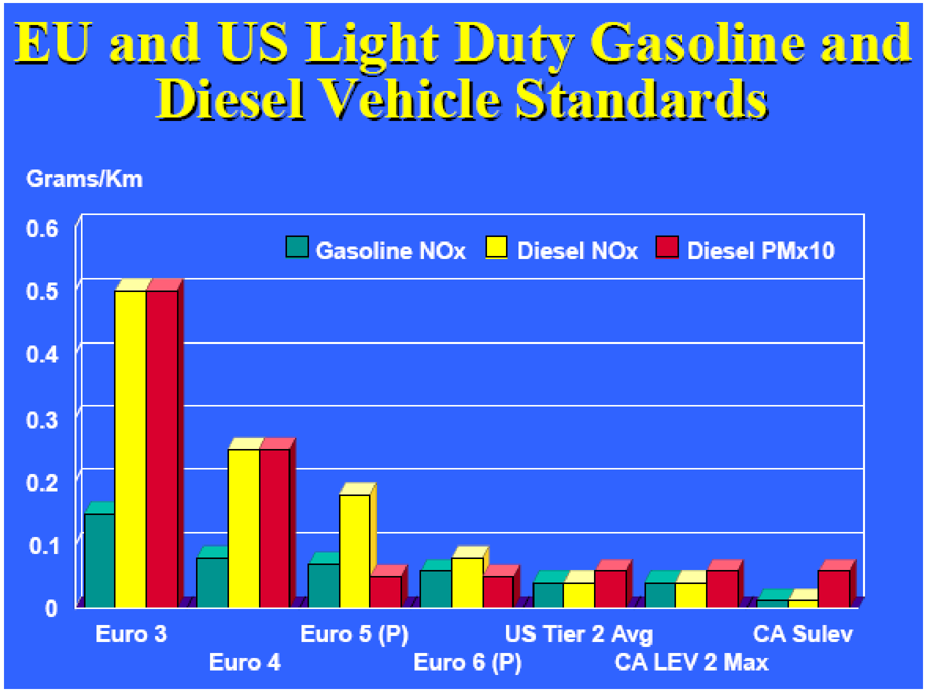
	Fresh Ash Oil	Aged (500 hrs) Ash Oil
Ash Content, mass %	1.69	1.83
Sulfur Content, wt%	0.921	0.889



Some of the ash from consumed lube oil goes back to the sump.



Regulations Differ by Region


EU and US Light Duty Gasoline and Diesel Vehicle Standards

Note the advantage given to diesel in Europe relative to NO_x

This partially explains the clear difference in market share of diesel vehicles in these two regions

Source: Michael P. Walsh

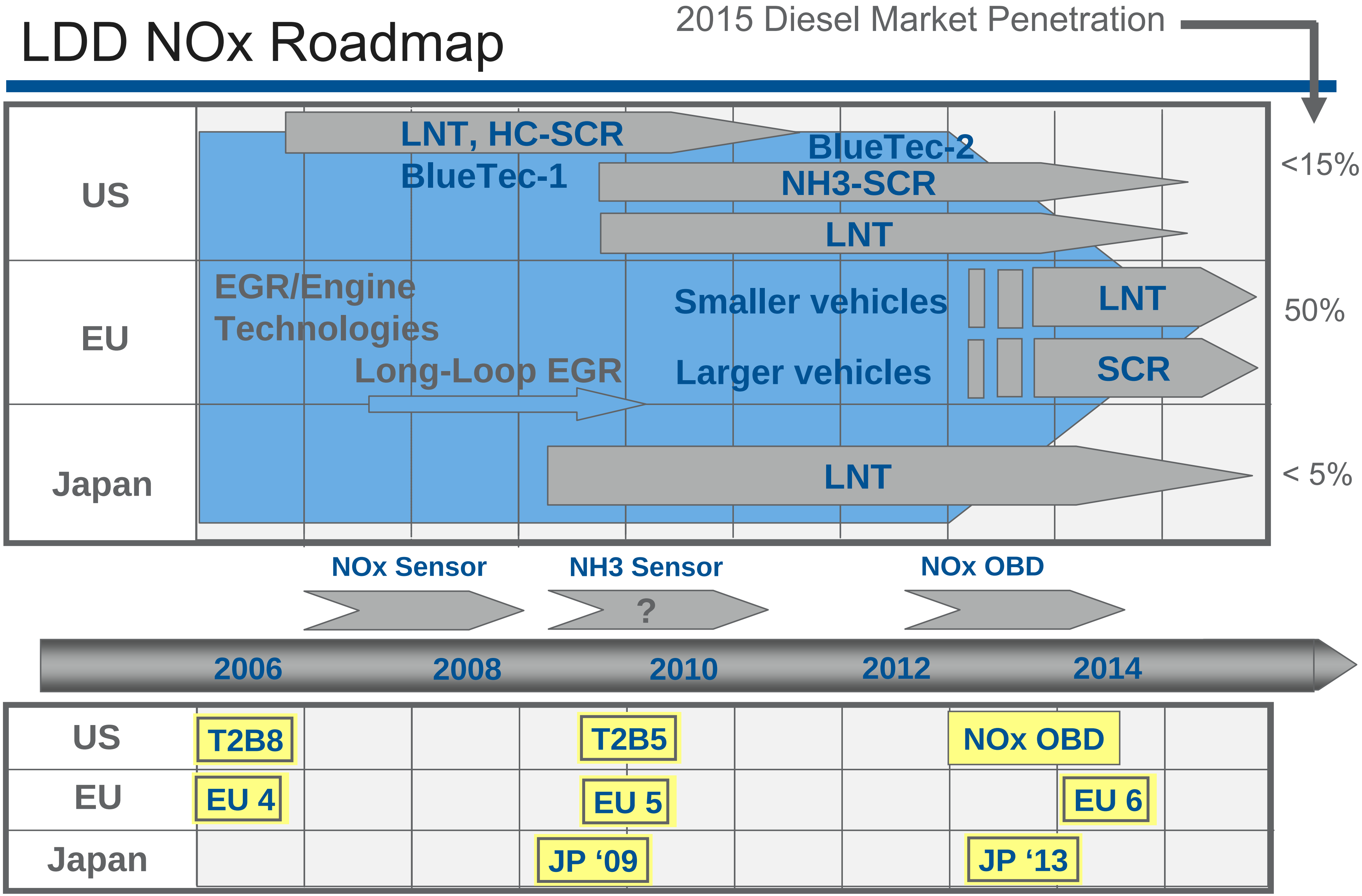
	2005 Tier 2, MDPV*	2005 Tier 2, Bin 9*	US Tier 2 Bin 5	CA Lev2, ULEV	Euro 4	Euro 5**	Euro 6***	Japan '05	Japan '09
NOx g/km	0.9	0.3	0.03	0.07	0.25	0.18	0.08	0.14/0.15	0.08

* MDPV Medium Duty Passenger Vehicles (>8,500 lb) must comply with Bin 5 standards beginning with 2009 model year

** Euro 5 standards (model years 2009/10+)

*** Euro 6 standards recently fixed (model years 2014/15+)

LDD NOx Roadmap



2015 Diesel Market Penetration

US

LNT, HC-SCR

BlueTec-1

BlueTec-2

NH3-SCR

LNT

<12%

EU

EGR/Engine Technologies

Long-Loop EGR

Smaller vehicles

LNT

Larger vehicles

SCR

50%

Japan

LNT

< 5%

NOx Sensor

NH3 Sensor

?

NOx OBD

2006

2008

2010

2012

2014

US	T2B8	T2B5	NOx OBD
EU	EU 4	EU 5	EU 6
Japan		JP '09	JP '13

Summary

"DPFs are becoming as much a part of the modern diesel engine as direct injection and turbocharging." Ulrich Dohle, President Bosch Diesel, 2006.

- Diesel system trends described
- Sophisticated regeneration control strategies emerging
- Materials and filter design optimization in progress
  - Three major DPF materials in the market
  - Pore size effects on filtration efficiency (~ 20 µm threshold)
  - Wall attributes, cell structure, and cell density
  - Ash management
- NOx aftertreatment trends and complexity being addressed