

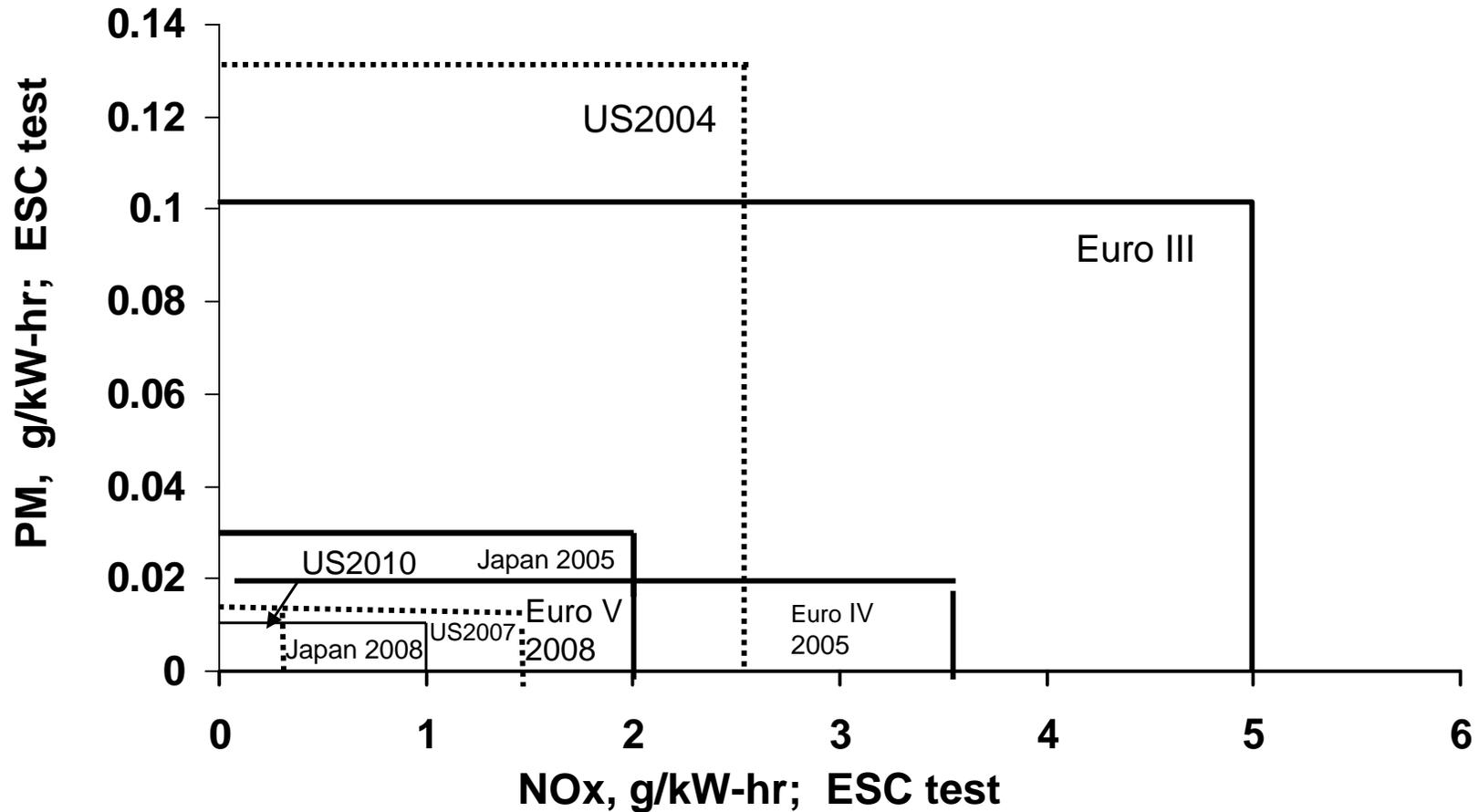
# Update on Diesel Exhaust Emission Control

Tim Johnson  
August 26, 2003

# Regulations and Approaches

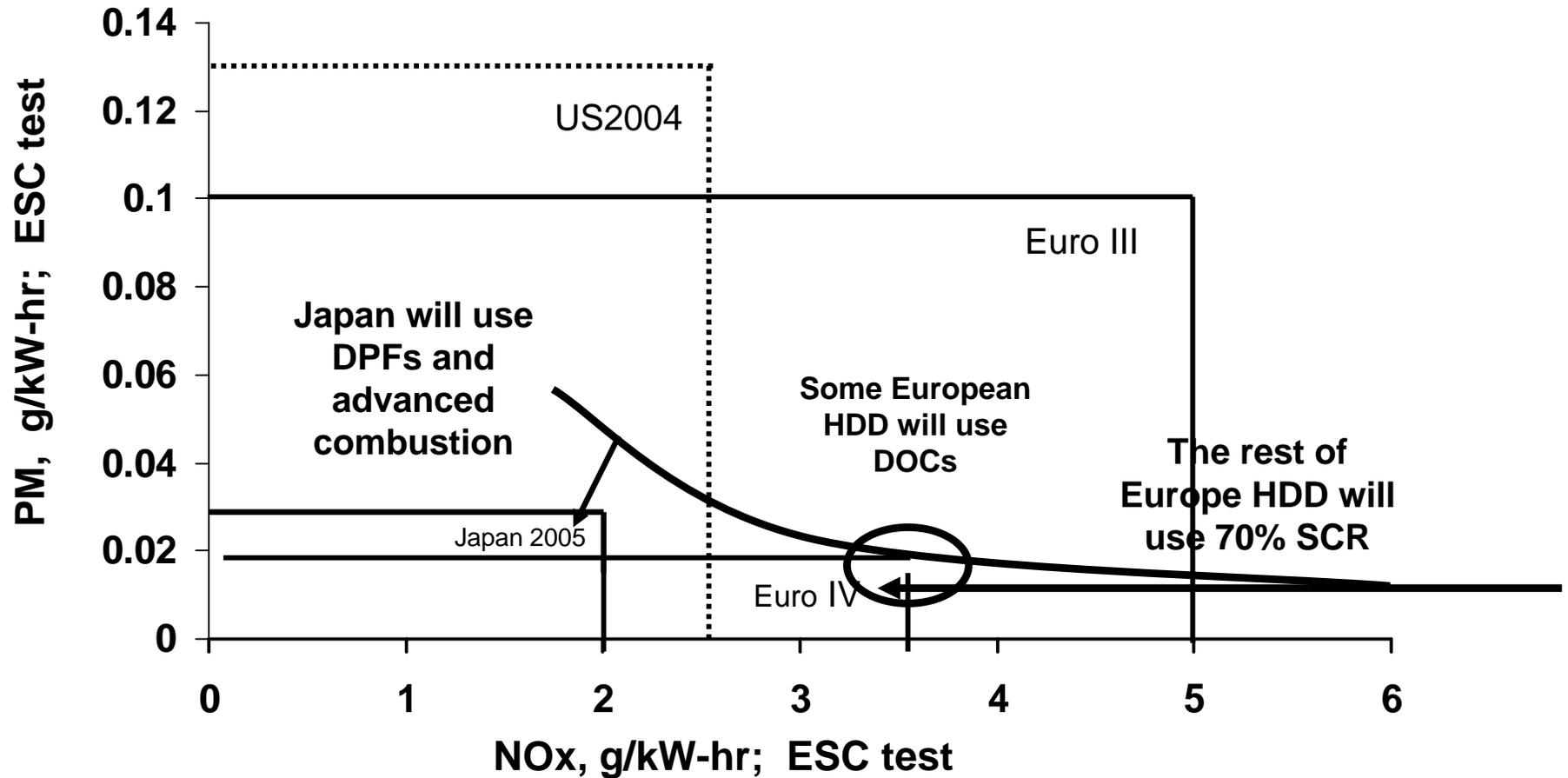


# Euro IV and Japan 2005 are coming next, with significant PM and NOx tightening; US2007 goes further; US2010 very low;

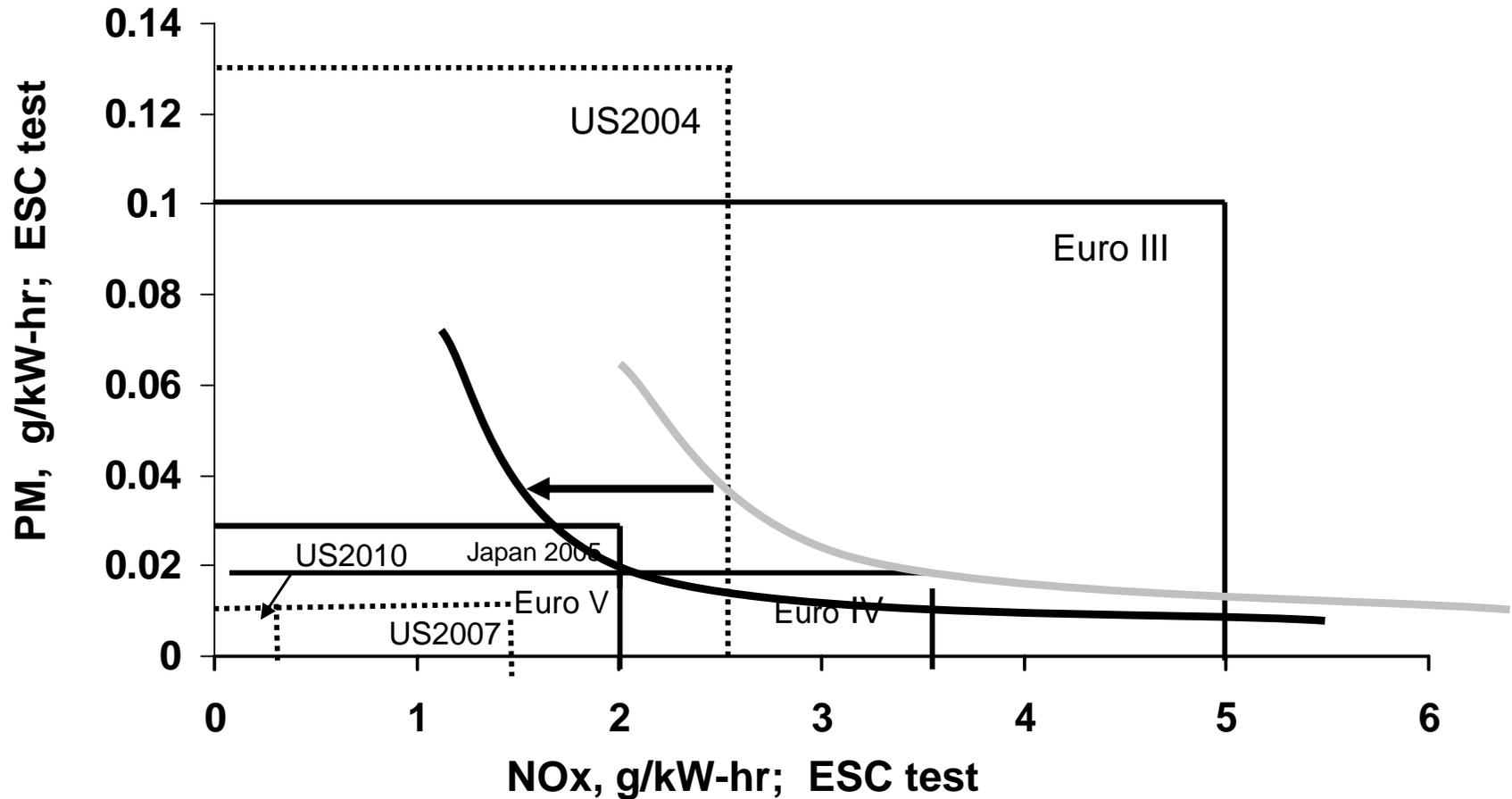


New: German/French Euro VI (2010) proposal is 0.5 g/kW-hr NOx and 0.002 g/kW-hr PM

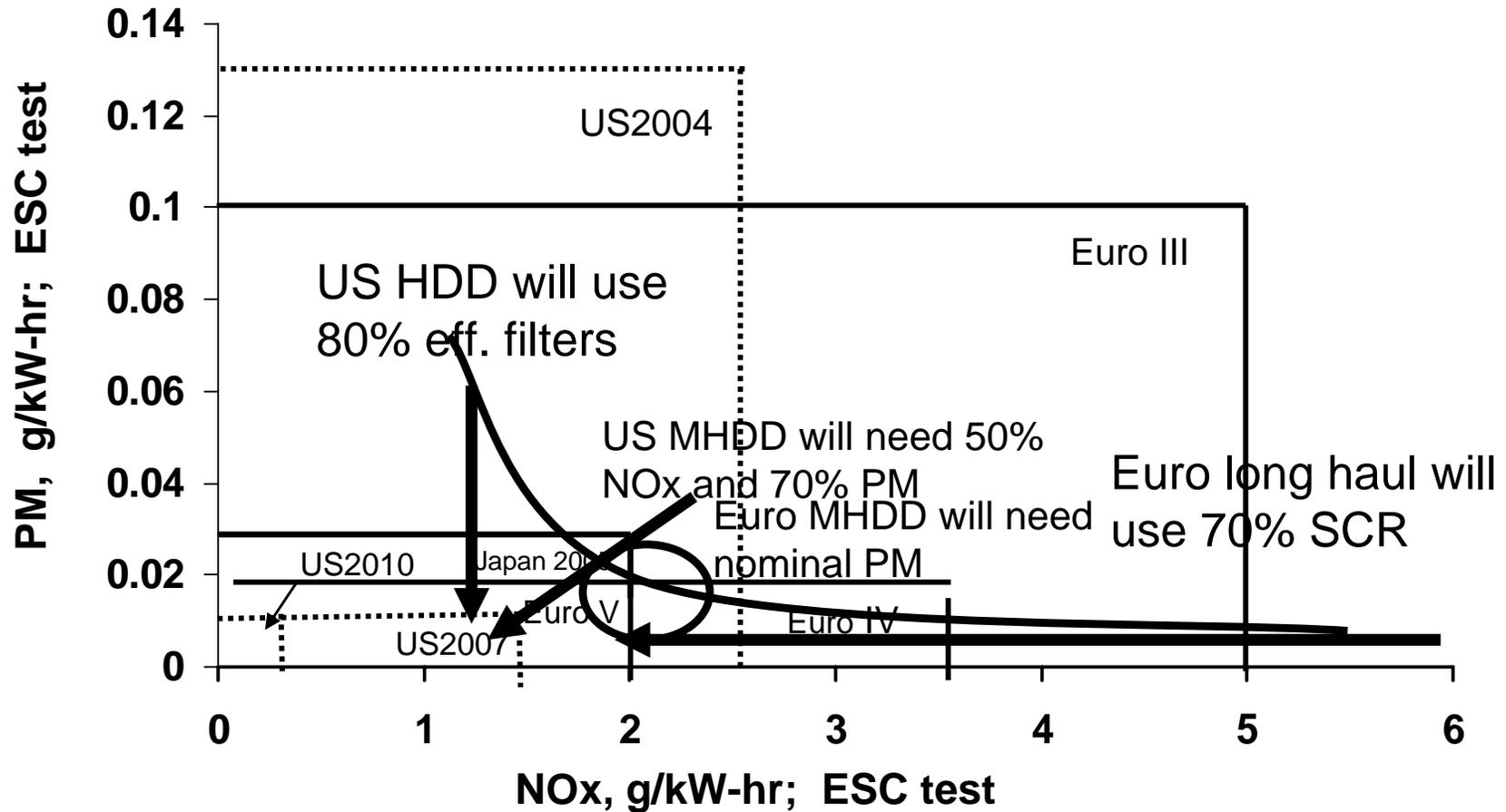
# In 2005, filters, DOCs, and SCR will be used



# By 2007+, engine technologies are expected to make significant advances



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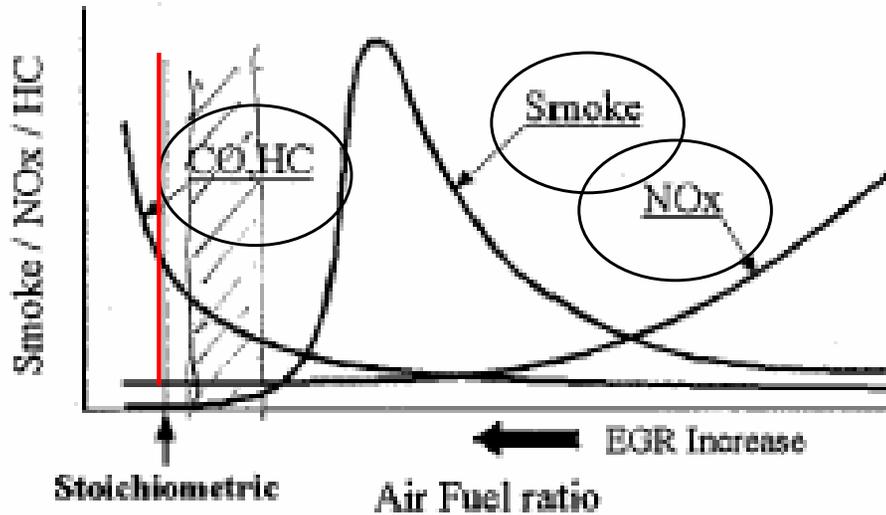




# Recent developments in filters

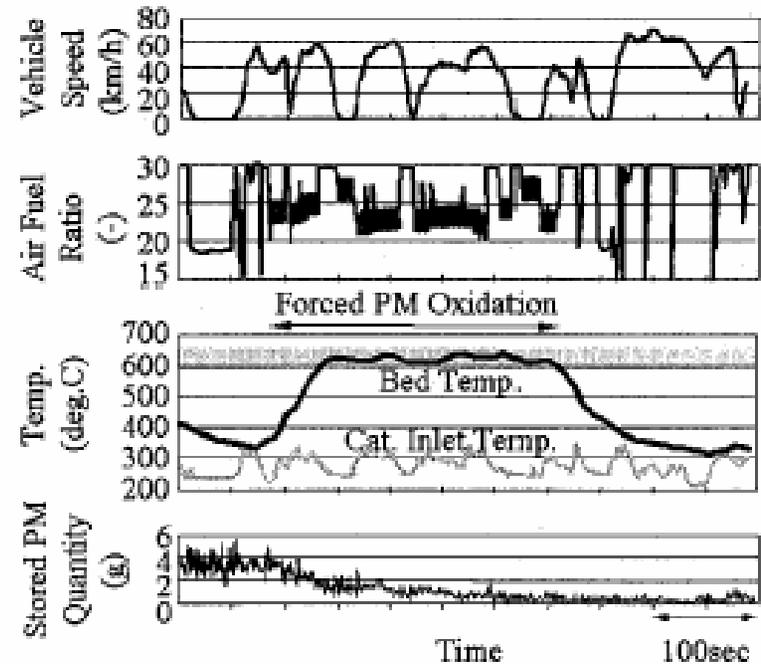


# Low temperature combustion is being used in LDD to regenerate DPFs



Low load combustion strategy uses high EGR to burn slightly lean to generate CO&HC with low NOx and PM

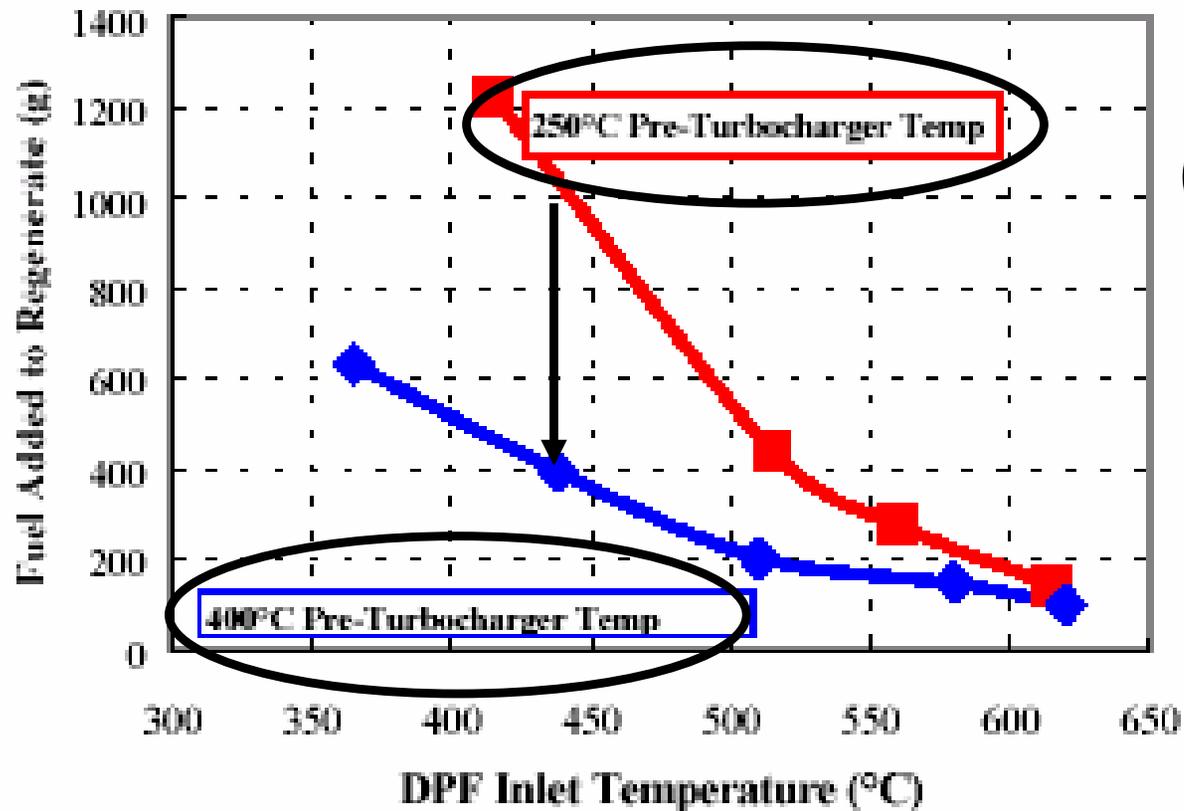
- This strategy, HCCI, and VVT offer attractive LT DPF regeneration options.
- They will not be implemented widely until 2007 or beyond in HDD
- LTC is being used in LDD this year.



Catalyst inlet temperatures of 200 to 320C are reported that will heat CDPF (DPNR) to >600C under low load

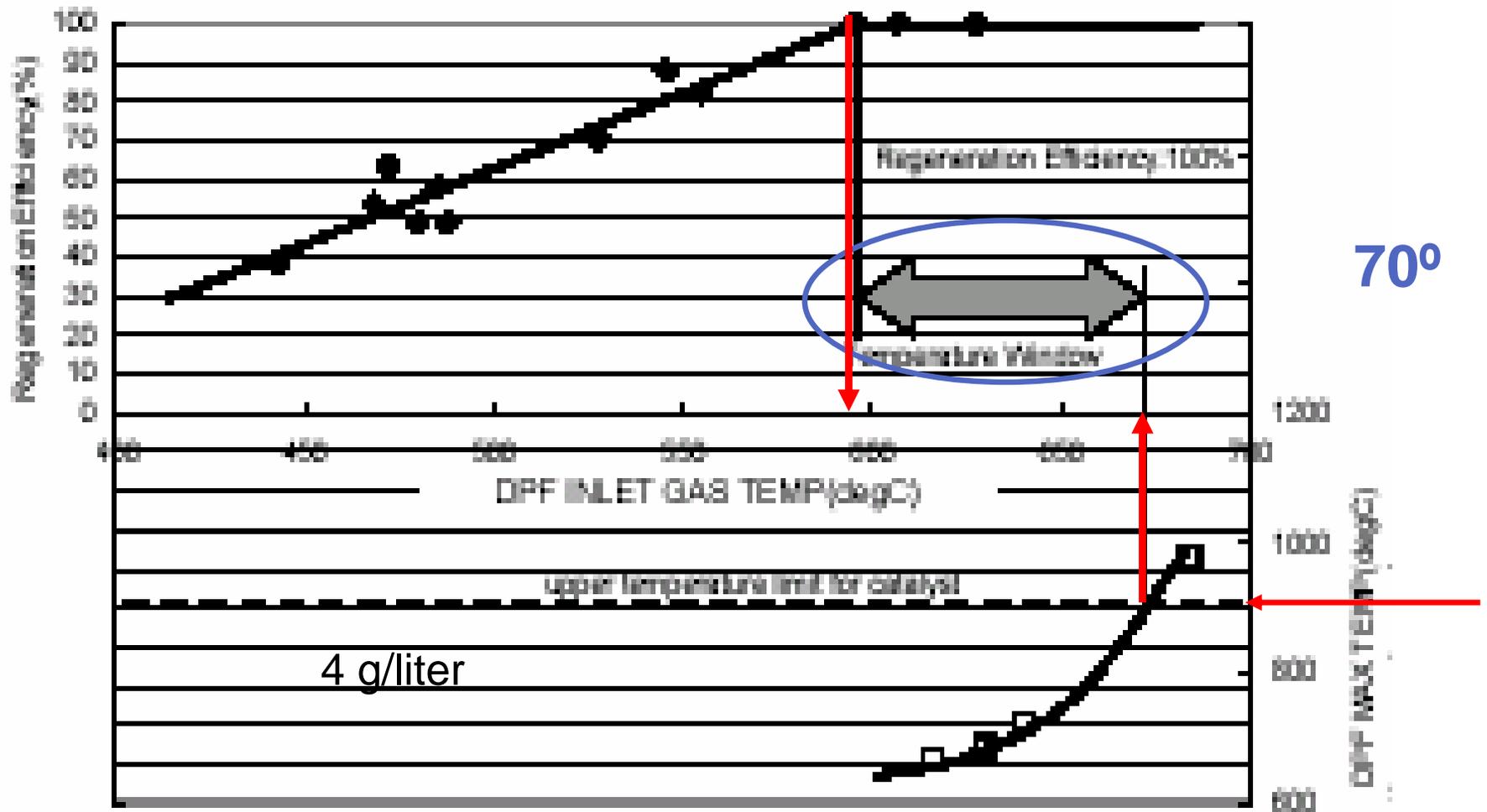
Toyota, JSAE 5/03

# DPF regeneration fuel savings can be realized with post injection using higher exhaust temperatures

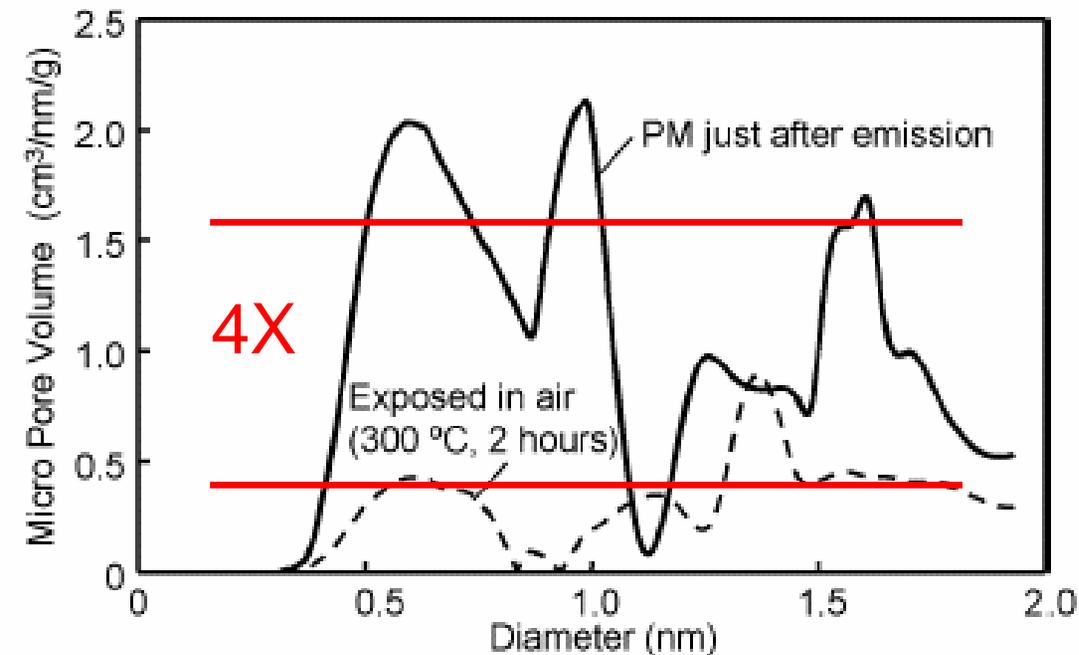


Although it takes more fuel to increase exhaust temperature, a net fuel savings is realized for DPF regenerations at higher T.

# Safe regeneration characteristics of catalyzed SiC filter systems are characterized

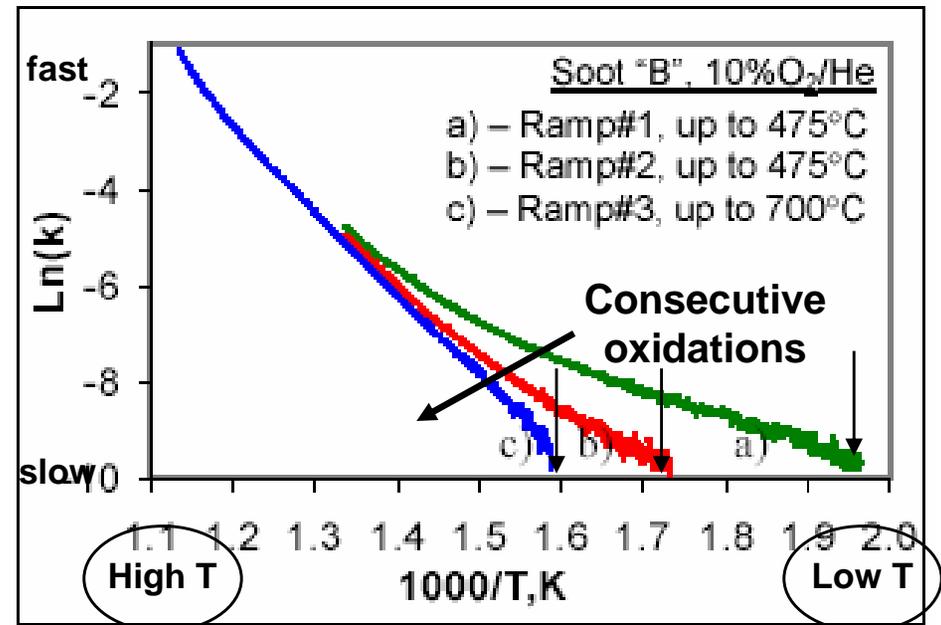


# Perhaps filter regenerations should be done more frequently to take advantage of highly reactive, fresh soot



Fresh soot has more micropores than older soot

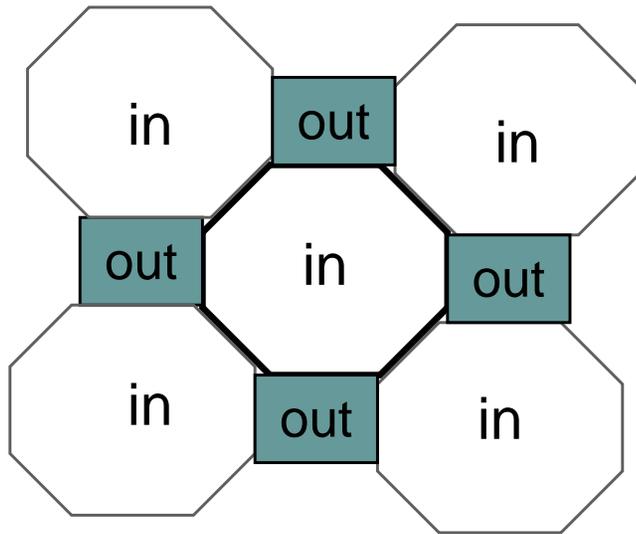
Toyota SAE 2002-01-0957



Fresh soot is more reactive than older soot

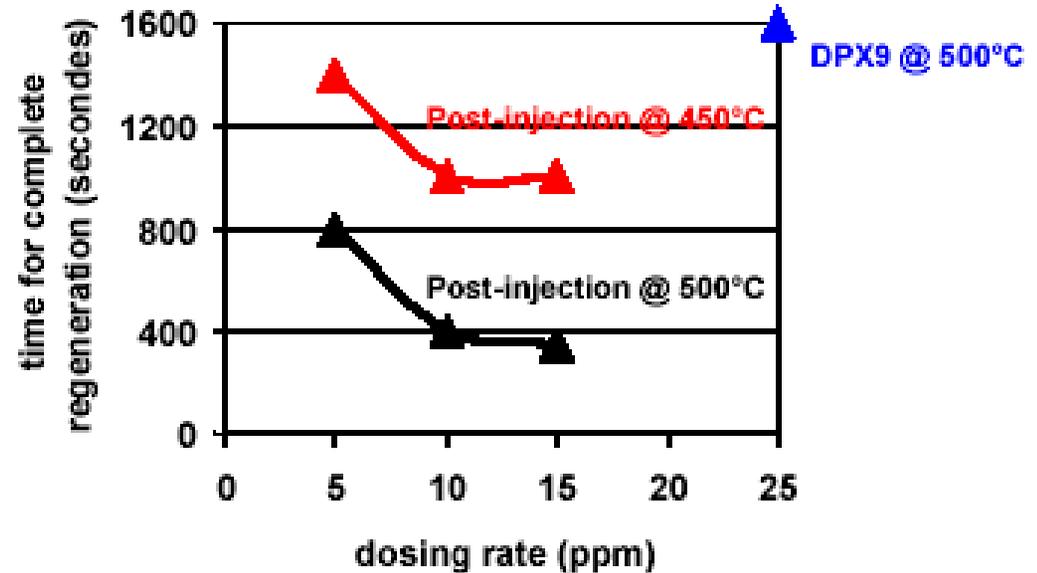
Cummins, SAE 2003-01-0833

# Ash cleaning not needed for life of vehicle with new filter design; 2nd generation Ce-based FBC performs better at lower dose rate;



Ash storage capacity increases 2X with larger inlet:outlet ratio in DPF

(PSA, ETH Particulate Conf. 8-03)



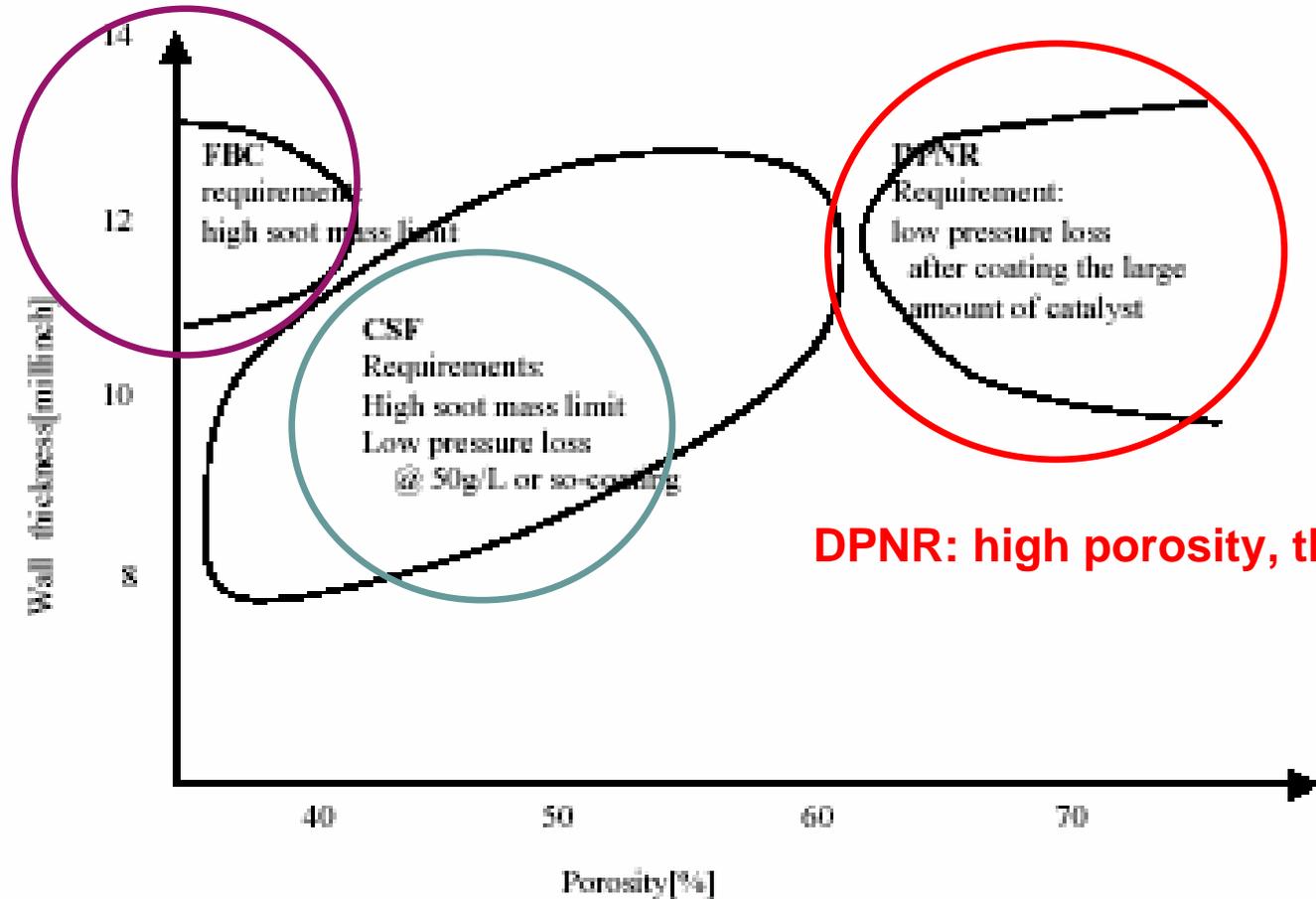
Reservoir requirements dropped from 5 to 1.5 liters, lasts 50% more (120,000 km)

Rhodia SAE 2002-01-2781

# Pore structure can be engineered for the application

**Uncatalyzed: narrow pore size, low porosity, thick walls**

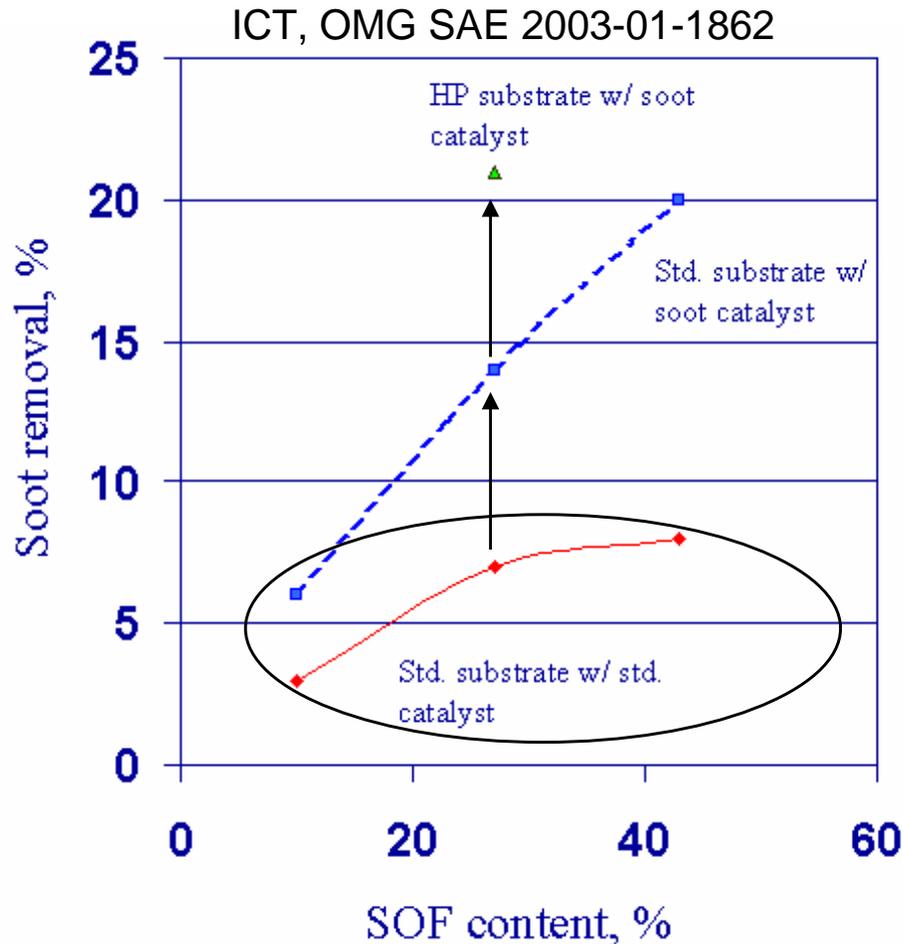
**Catalyzed: broad size distribution and porosity, range of wall thickness**



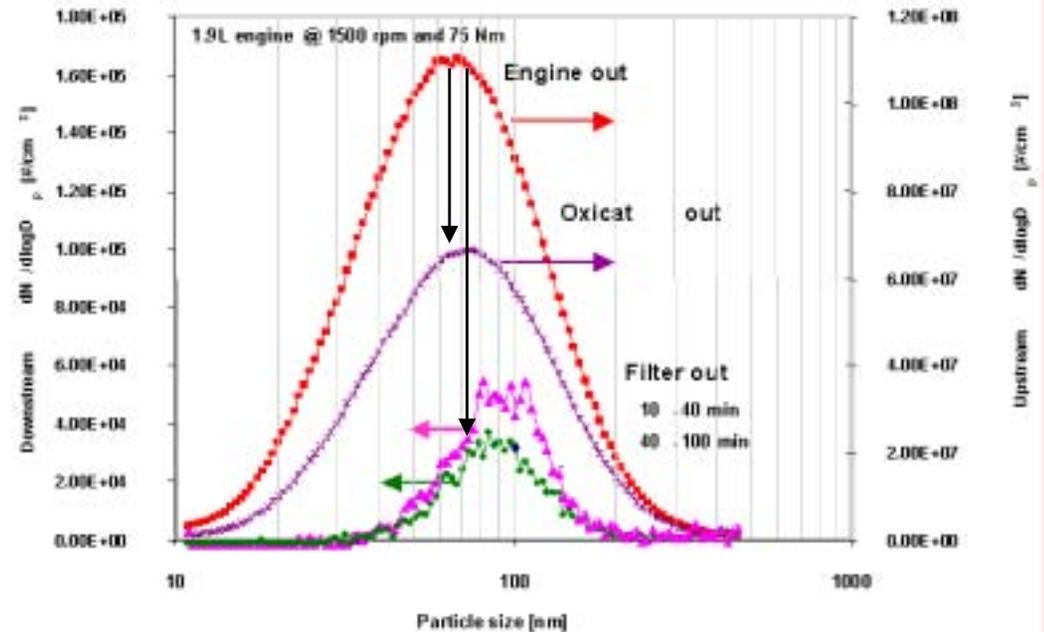
**DPNR: high porosity, thick walls**

Ibiden SAE 2003-01-0377

# Optimized flow-through oxidation catalysts can remove soot



Soot removal efficiency depends on exhaust SOF content. Hypothesis is SOF condenses on catalyst and brings soot with it. High porosity substrate (65%) enhances soot/catalyst contact.

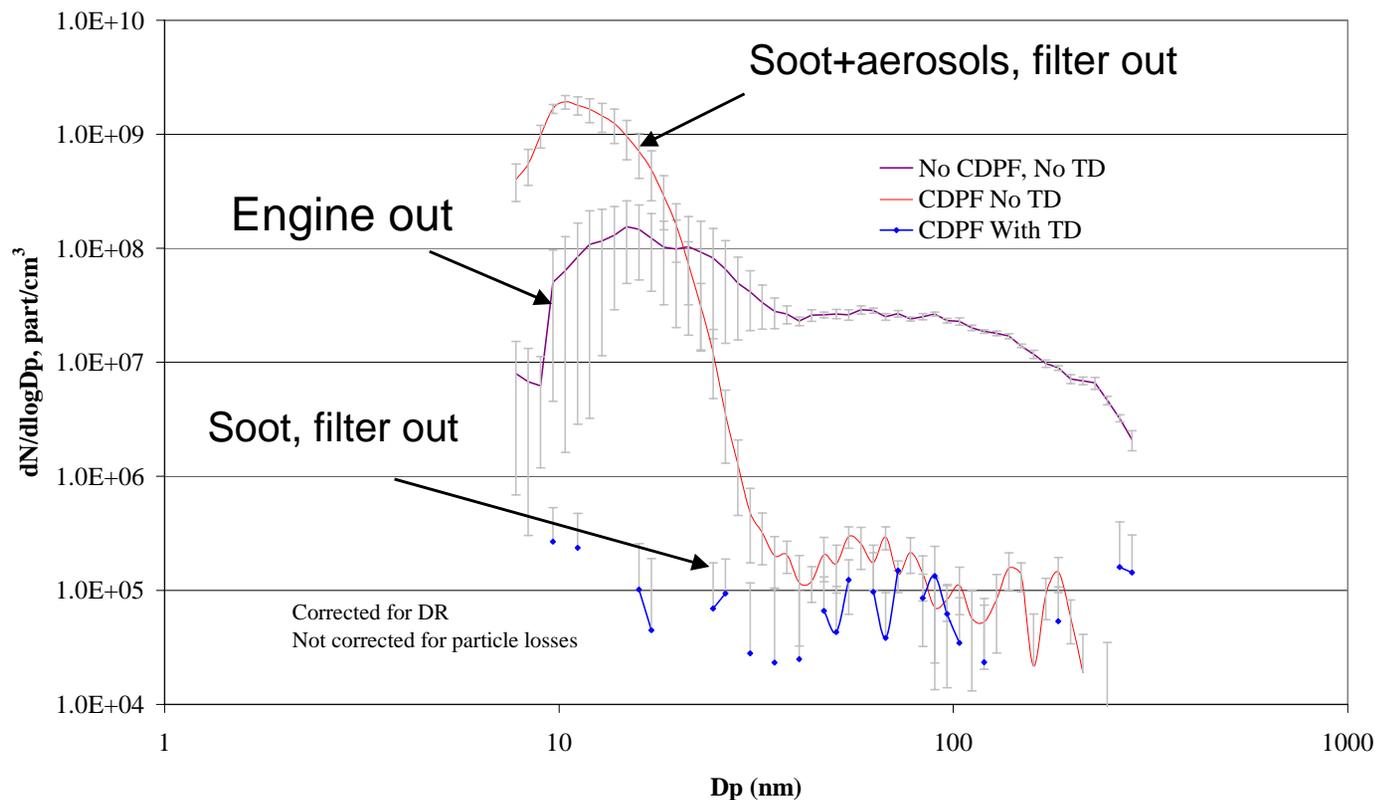


Oxidation catalysts drop ultrafines by about 30%. DPFs by 99.9%.

CERTH/CPERI, ETH Particulate Conf. 8-03

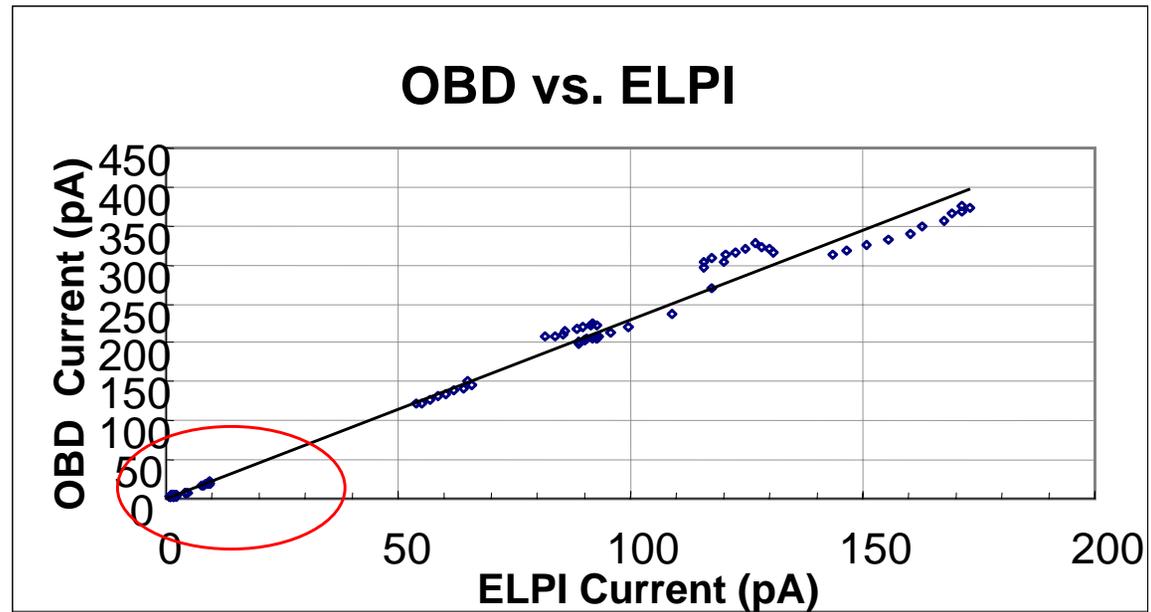
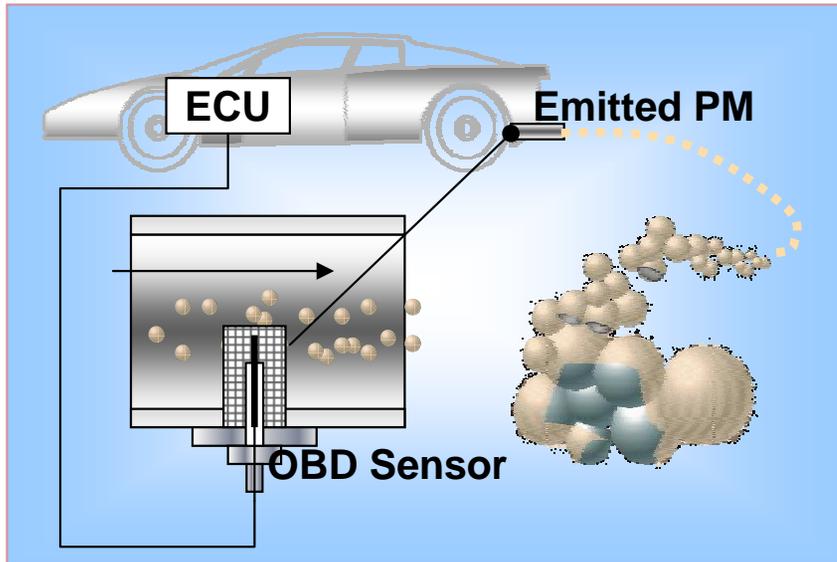
# Filters are very effective in removing carbon ultrafines; under high load conditions, DPF can form nanoparticles

Fuel Sulfur Tests: Cummins CVS, ISM Engine, 1200/1927 N-m,  
Specially Formulated Lube Oil,  
26 ppm S Fuel With and Without CDPF, TD



With TD (thermal deneuder), carbon ultrafines are removed 2.5 orders of magnitude. However, emissions of aerosol nanoparticles goes up.

# PM OBD sensor is in early stages of development



**Operation: Electrical potential across flow charges particles. Difference between input current and ground is indicative of PM**

**Good correlation between OBD device and ELPI, even at very low PM levels**

# Thoughts on ash management

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- Some HD vehicles: 240,000 to 400,000 km without ash cleaning  
(BP SAE 2002-01-0433).
- Lube oils are reducing ash loadings by 30%
- Washing is okay to clean uncatalyzed filters.
  - Catalyzed filters: washing questioned and TBD.
- Central facility is okay for uncatalyzed filters.
  - problematic for catalyzed filters
- Filter design can minimize ash cleaning intervals



# NOx Control

# LNT and SCR lead the field on effective NOx control, but LNC showing improvement

System	Transient Cycle NOx Efficiency	Effective Fuel Penalty	Swept Volume Ratio	Notes
SCR, 400-csi	85-90%	2-3% urea or about <b>1.5%</b> penalty in US	1.7 emerging	Being applied and specs being finalized; low temp. performance issues;
LNT	80-95%	1.5 – 4% total regen. + desulf.	1.3 to 2	Desulfation strategy and durability issues; integrated DPF/LNT components emerging; <u>PGM cost issues</u>
DeNOx catalyst	20-60%	2 to 6%	0.85 to 4	Generally not sensitive to sulfur; HC slip issues; durability needs proving

# SCR



# SCR is emerging as a possible solution to US2007

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- Two engine manufacturers recently announced serious intentions, subject to internal review
  - ATA seems interested
- EPA concerns
  - 150,000 mile maintenance-free emission control systems
    - might be addressed by certification with empty urea tank
  - undo hardship on operators in filling with urea
    - need viable infrastructure

# 77% of diesel is pumped at 2200 stations

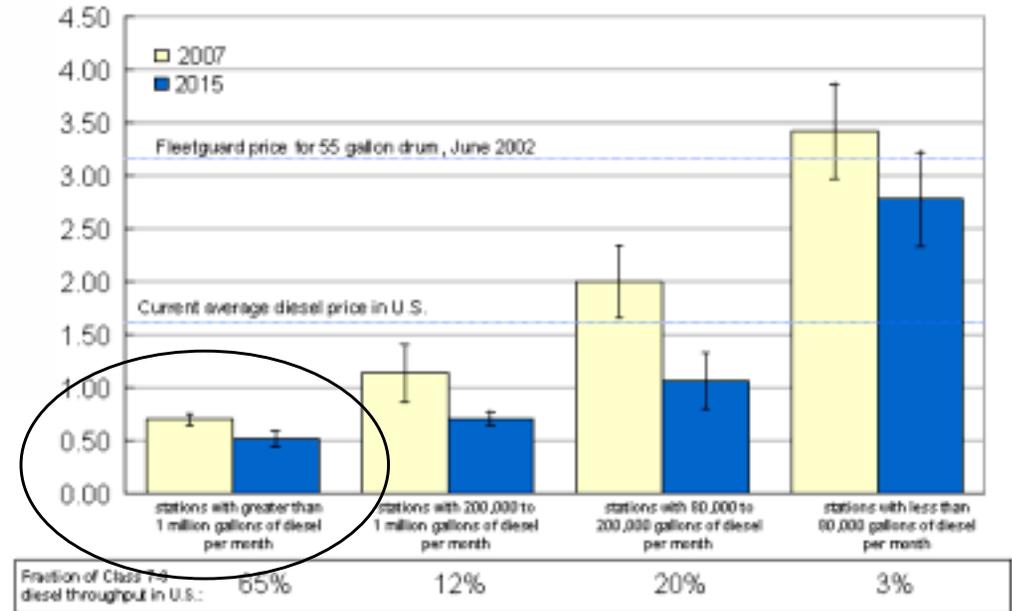
## Profiles of Fueling Stations Serving the Class 7 & 8 Truck Market

Station Size (Monthly Diesel Consumption)	# of Public & Private Stations	Diesel Consumption
<b>Large</b> (2,000,000 – 1,000,000 gal/month)	2,200	77%
<b>Medium</b> (200,000 – 80,000 gal/month)	3,500	20%
<b>Small</b> (<80,000 gal/month)	>25,000	3%

2200 stations pump 77% of fuel;  
additional 3500 bring total to 97%

To make infrastructure viable, estimates  
are that about 50% of 2007 trucks would  
need SCR

## Retail Urea Cost By Diesel Station Throughput

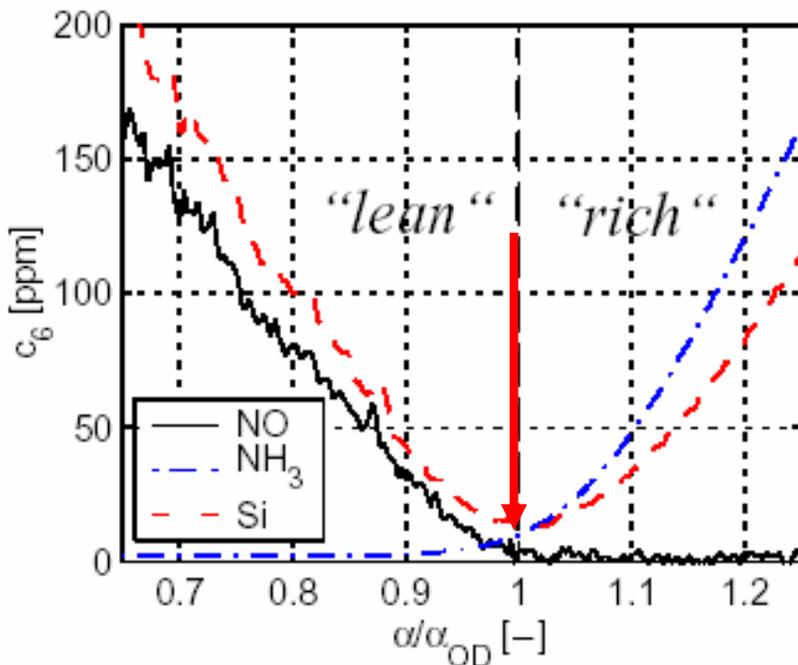
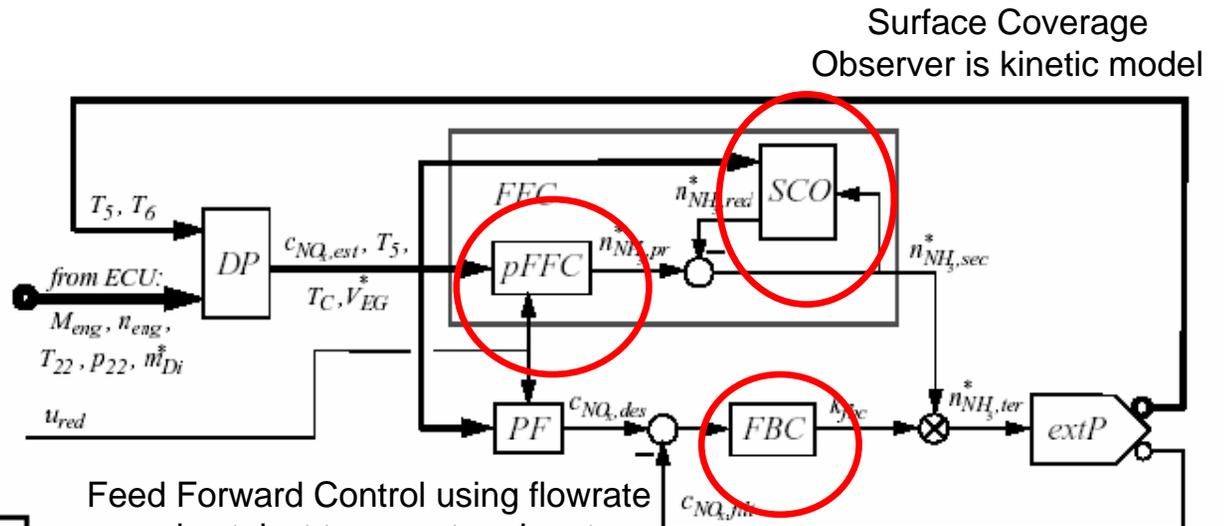


Urea could cost \$0.70/gal at the largest 65%  
of truck stops

# A urea control strategy incorporates feed forward and feed back control

ETH, SAE 2003-01-0776

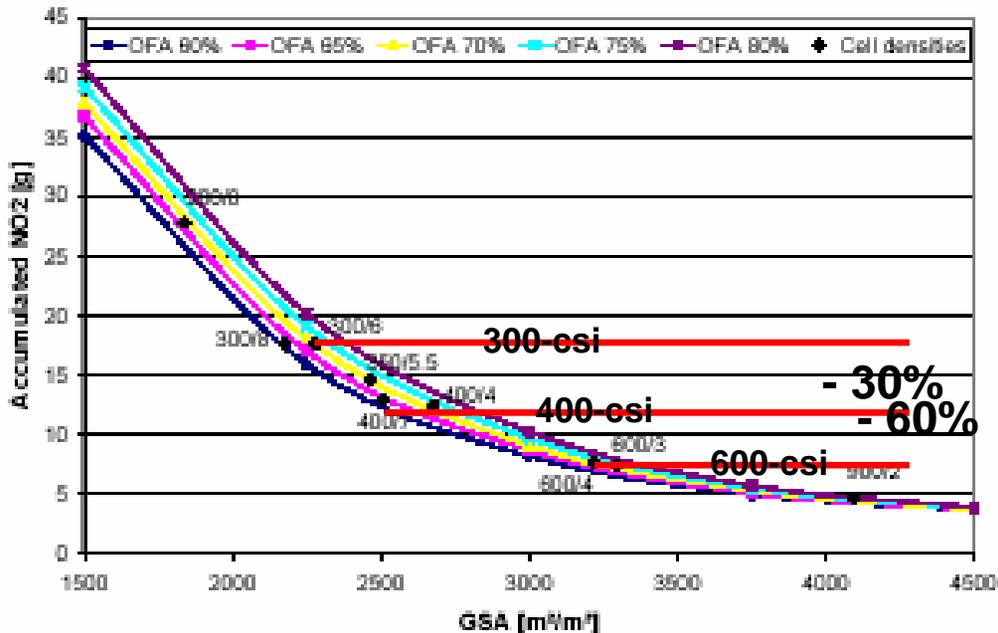
10 liter turbocharged intercooled engine; 2 liters coated SCR catalyst; NOx sensor at exit



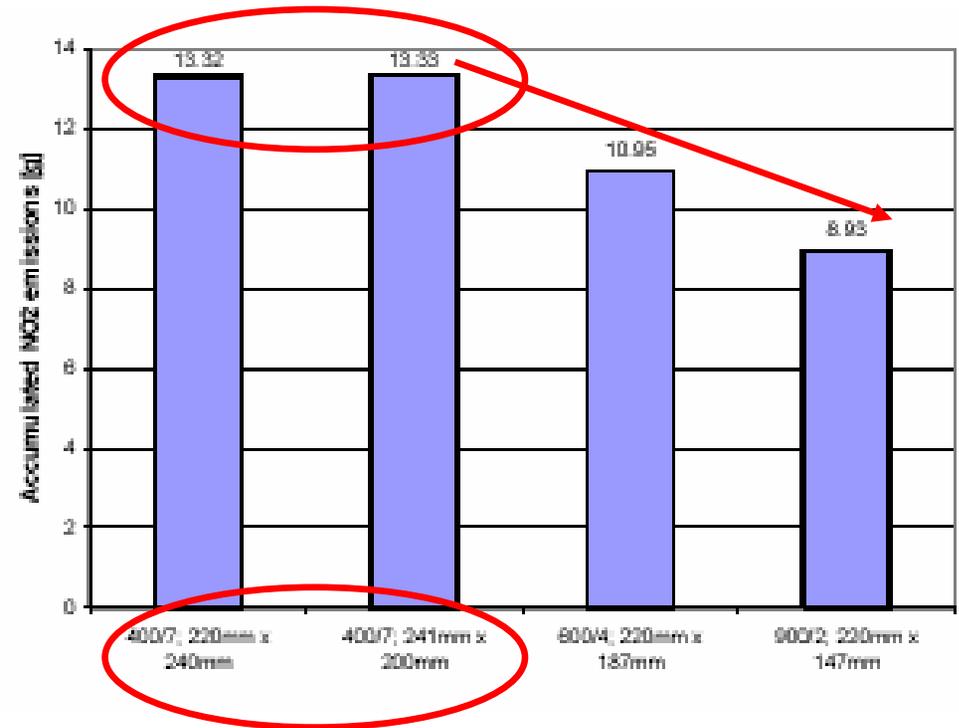
Given temperature constraints, FBC is not needed for ESC; all aspects are used for ETC; >80% efficiency, <10 ppm slip

# A dynamic model is developed to optimize the cell density of SCR systems

Same volume, increasing cell wall area



Same cell wall area, decreasing volume



400-csi:  
Shorter, larger diam.,  
same emissions

600-, 900-csi:  
-22% and -40% volume,  
-18% and -33% lower emissions

# Lean NOx Traps

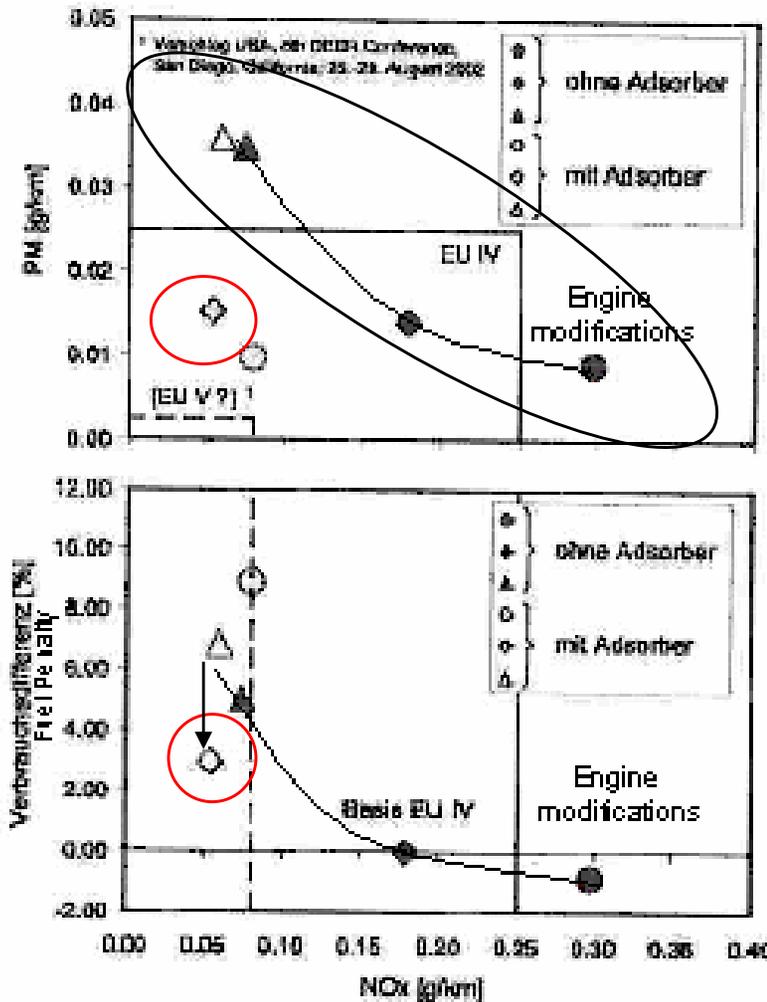


**CORNING**

Discovering Beyond Imagination

# LDD Emission requirements and fuel penalties are described for Euro V (Proposal)

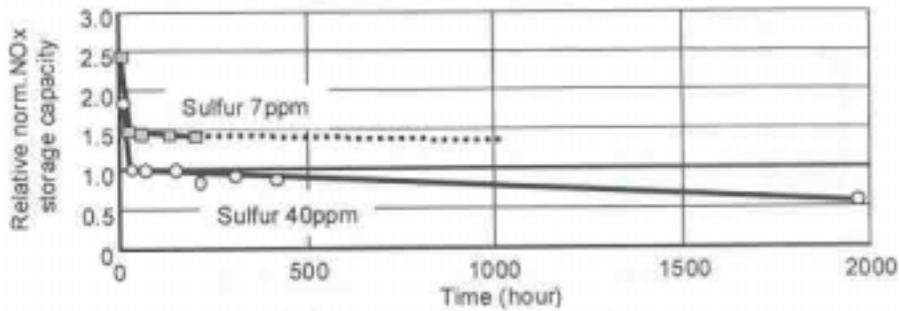
SCR has about a 7% effective fuel penalty to hit Euro V LDD



FEV, Vienna Motorsymposium 5/03

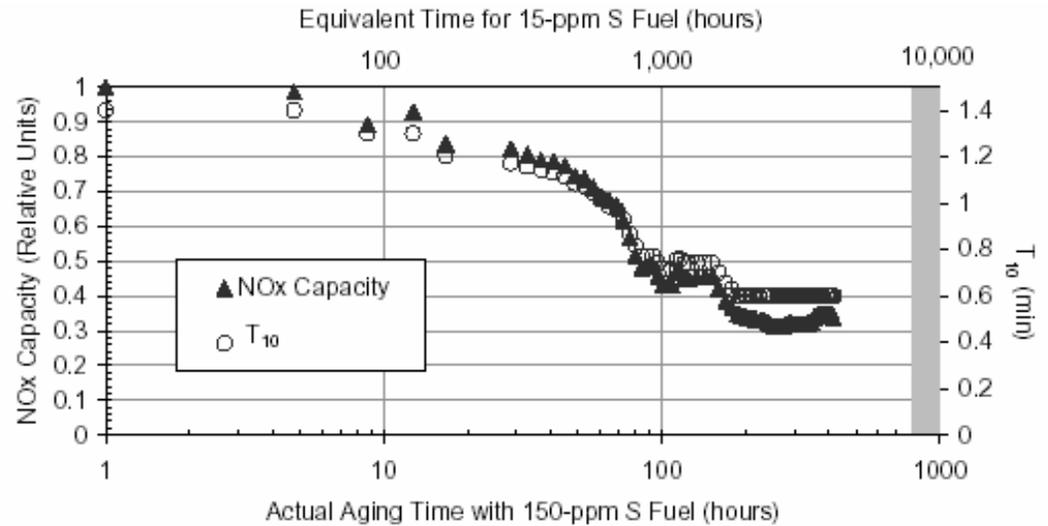
To hit Euro V NOx with LNT, a 3% FP is obtained, 5% via engine means.

# LNTs may deteriorate upon desulfation, but later stability is observed



Sulfur aging is characterized although not optimal 40-50 PPM is sufficient.

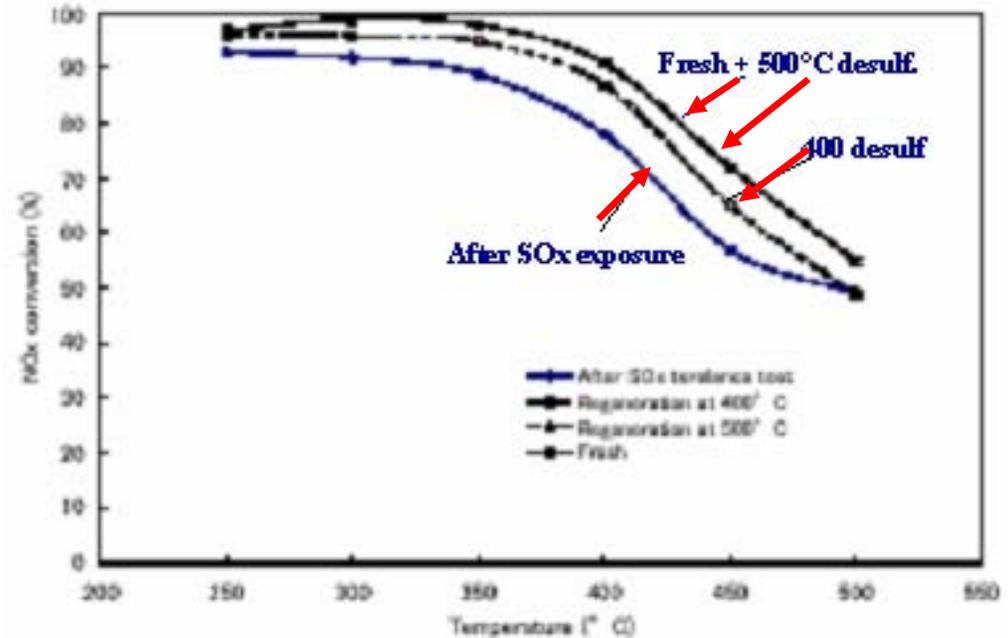
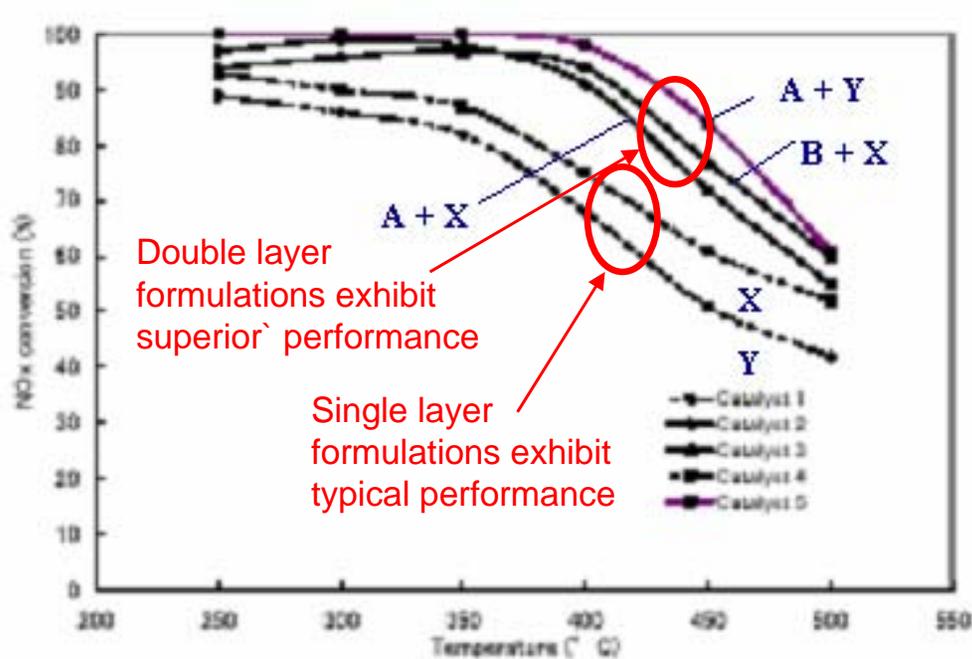
Toyota, Vienna Motorsymposium 5/02



Emerachem DEER 8/02 and SAE 2002-01-2880

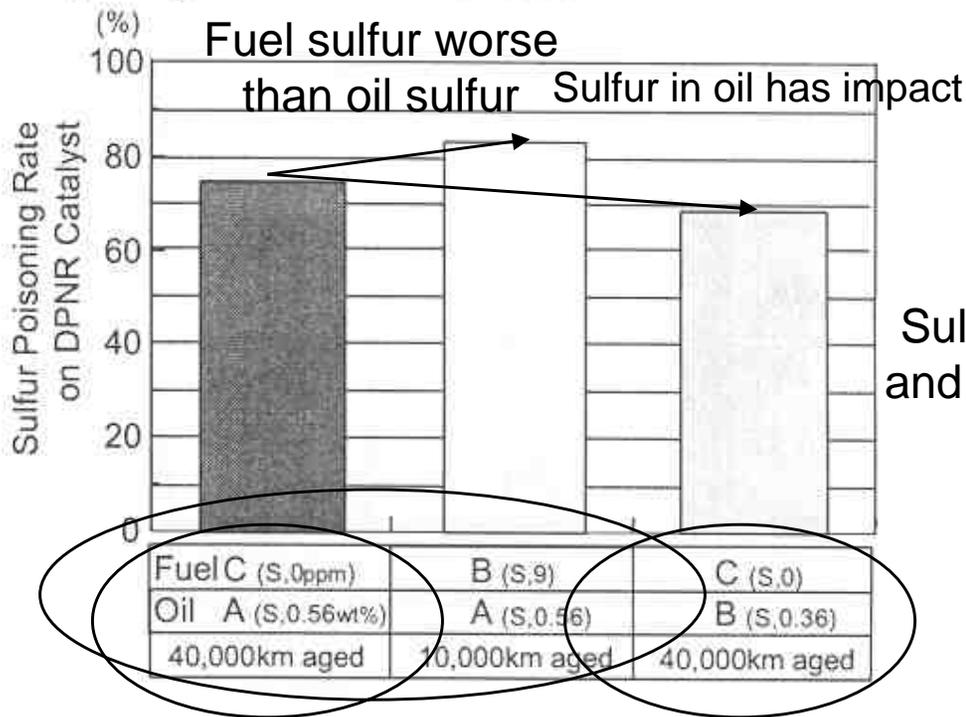
Other studies show no deterioration with up to 20+ desulfations. OMG Aachener Kolloquium 10/02; Delphi SAE 2002-01-0734

# A new double-layer LNT is developed that keeps SOx off the adsorbing material



Top layer adsorbs SO<sub>2</sub> for moderate storage capacity, but quick release.

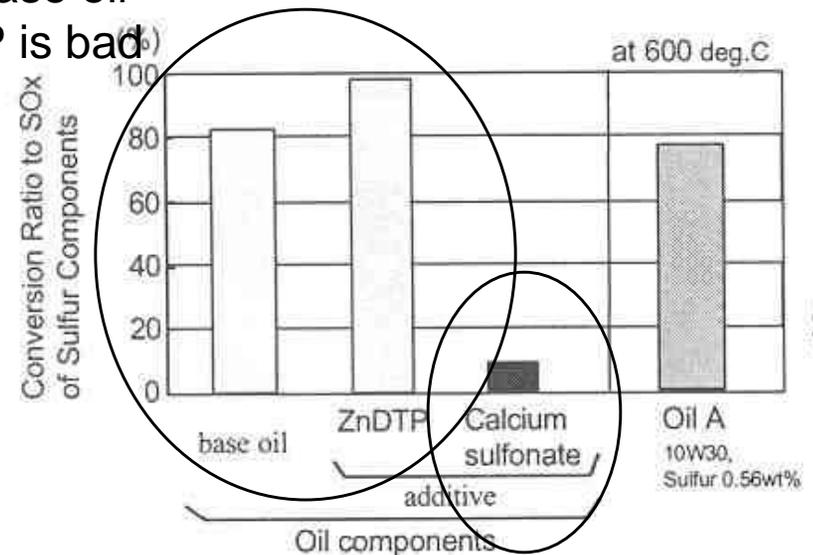
# Effects of sulfur in lube oil on LNT are quantified



Sulfur in base oil and ZnDTP is bad

Table 4. Test Oil Sample

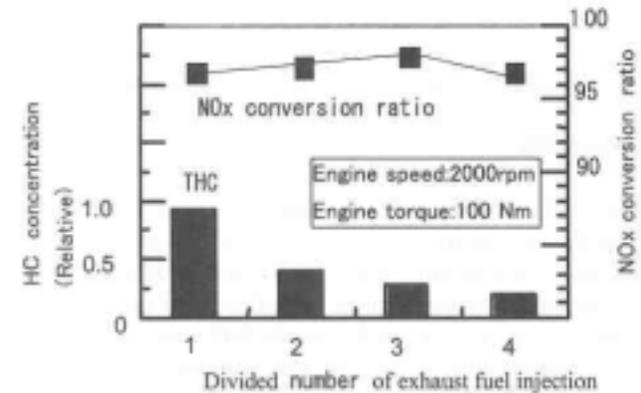
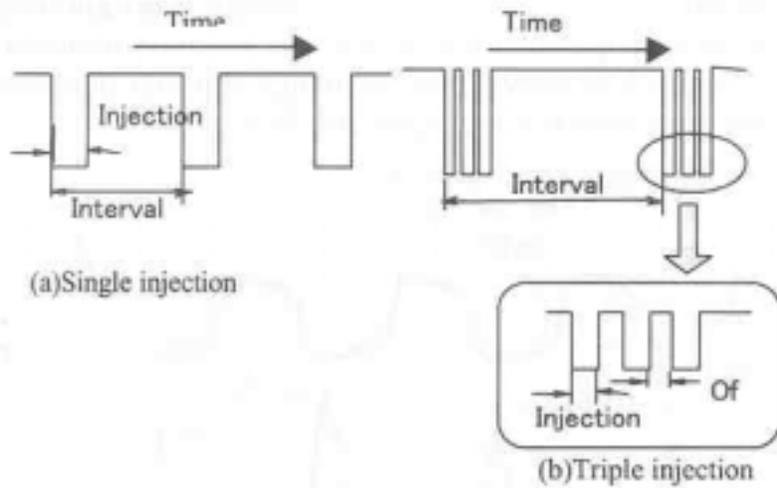
		Sulfur (wt%)
Base Oil		0.42
Additive with sulfur free base oil	ZnDTP	0.24
	Calcium Sulfonate	0.04



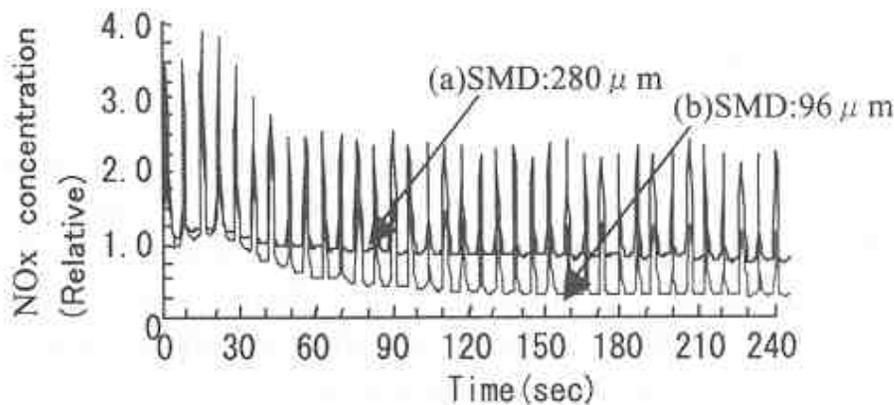
LNT efficiency is impacted by sulfur in the lube oil. Sulfur in base lube oil affect LNT more than sulfur in oil additives. A + B have same additive package.

SOx formation from lube oil varies on where the sulfur resides.

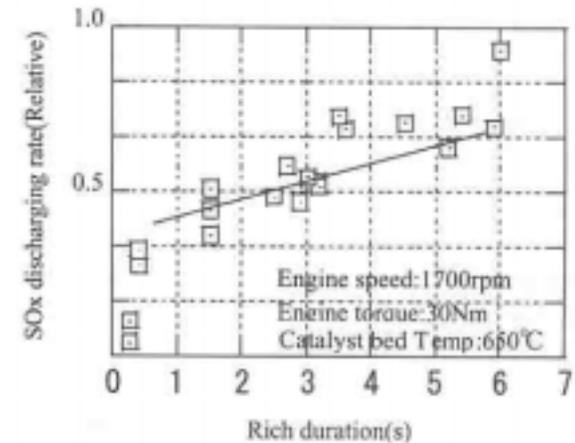
# Injection strategy for fuel is described for DPNR



Split injections result in better utilization of reductant and lower HC slip.



Smaller droplets from port injector evaporate faster, and are more easily utilized.



Given constant total desulfation fuel, it is better to have a longer rich pulse.

# Integrated systems



# DPF/SCR systems are on the road - 5 trucks in the US

SCR: extruded 200-csi, SVR=3.8

Exhaust Emission	Baseline (eng.-out)	SCR/DPF (cat.-out)	% of change
NOx (g/bhp-hr)	5.80	1.06	-82%
HC (g/bhp-hr)	0.055	0.00	-100%
PM (g/bhp-hr)	0.094	0.010	-89%
CO (g/bhp-hr)	0.71	0.40	-44%

Table 2. Combined FTP Testbed Exhaust Results, 2007  
 Combined FTP hit US2007 blended NOx and PM; 82% NOx efficiency, 89% PM efficiency

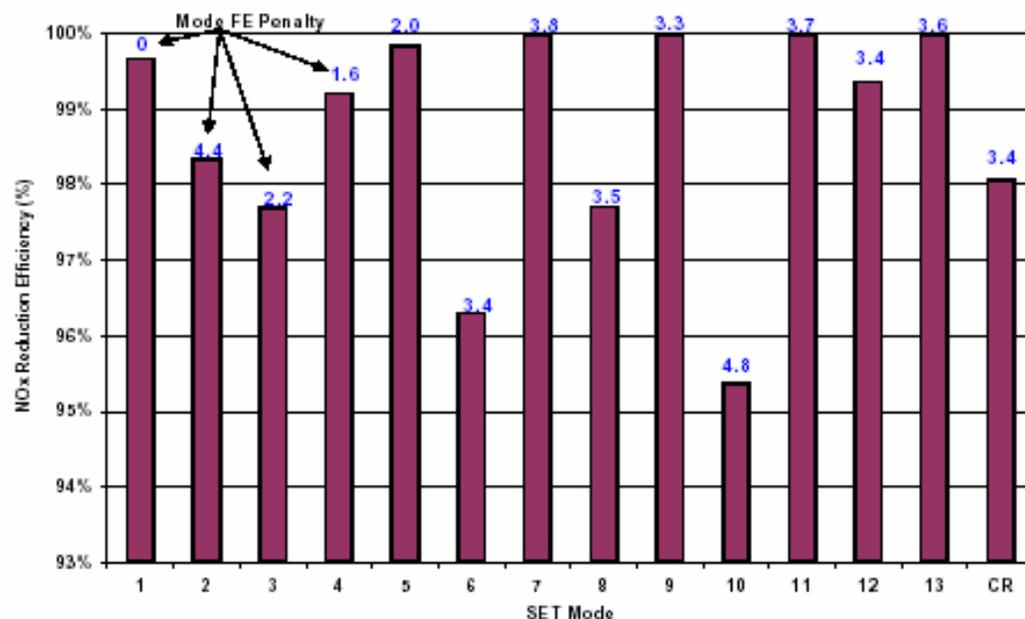
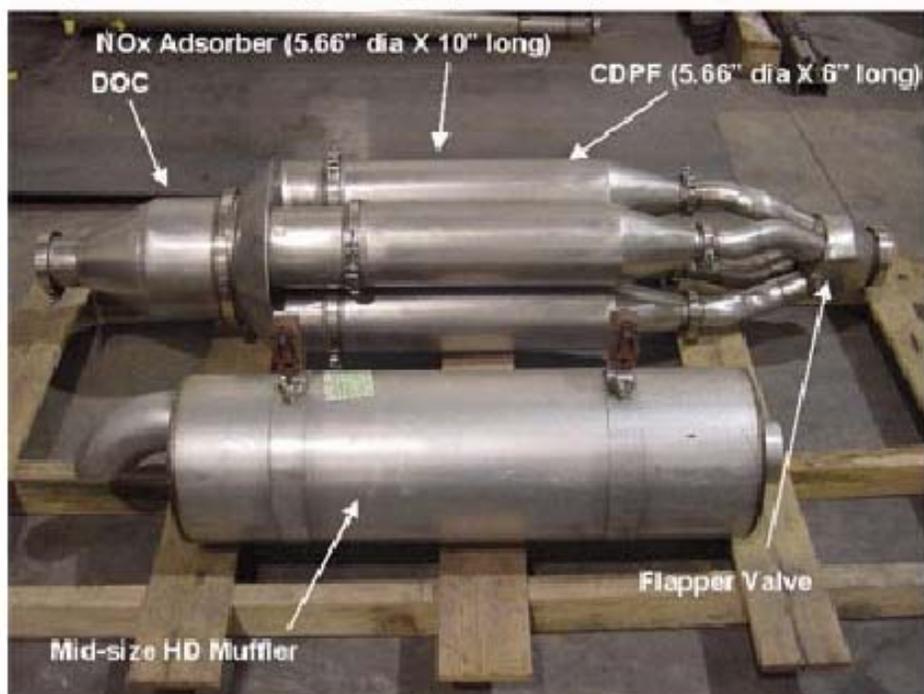
Exhaust Emission	Baseline (eng.-out)	SCR/DPF (cat.-out)	% of change
NOx (g/bhp-hr)	5.89	0.85	-86%
HC (g/bhp-hr)	0.01	0.00	-100%
PM (g/bhp-hr)	0.033	0.018	-55%
NH3 (ppm Ave.)	N/A	0.4	N/A

OICA hit US2007 transition NOx, but missed on PM due to sulfates



- 3 Mack highway tractor/trailers
- 2 refuse trucks
- started mid-2002

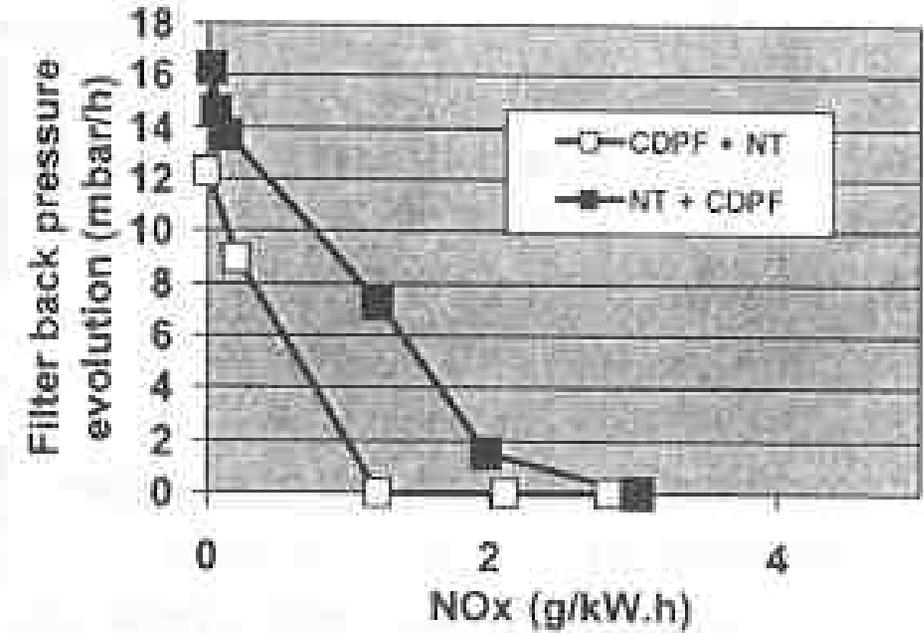
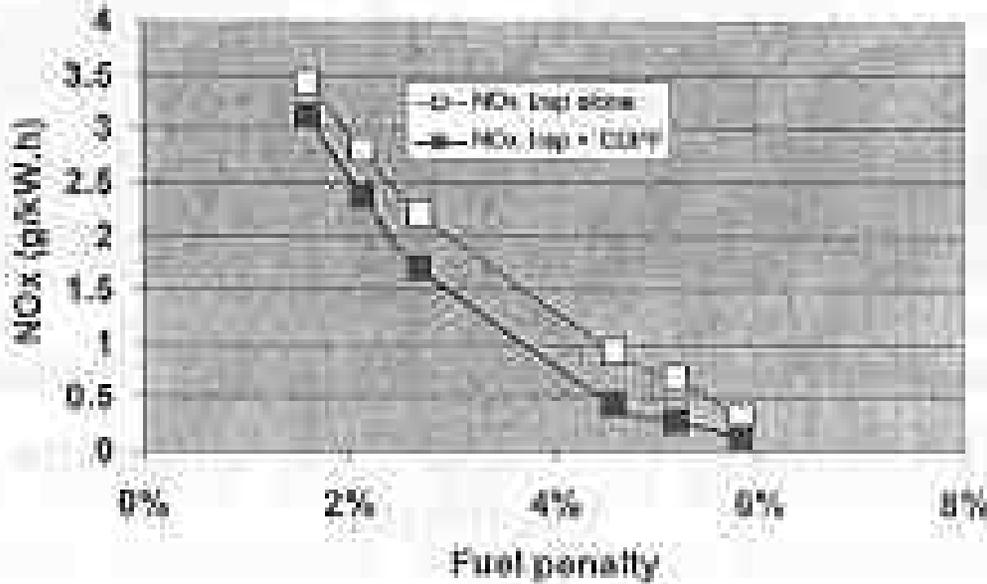
# The large EPA 2-leg LNT/DPF system is replaced with a more “efficient” 4-leg system



NOx efficiencies are >95% at all S.S. modes and fuel penalties are 1.6 to 4.8%.

In the EPA four-leg system, one leg is being regenerated while three legs are in collection mode. The regeneration gas is throttled and uses a fuel injector to minimize fuel penalty.  
 SVR (LNT) = 2.8; SVR (filter) = 1.7

# 6.2 liter Euro III HDE equipped with CDPF + LNT hit HDD Euro V; 1.8% FP



FC is lower with CDPF due to some downstream NOx conversion in it.

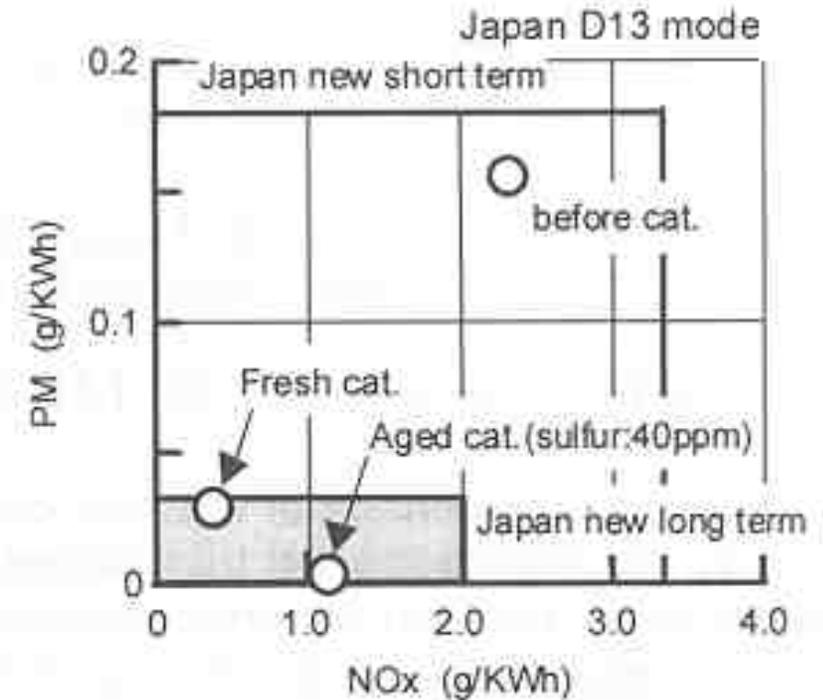
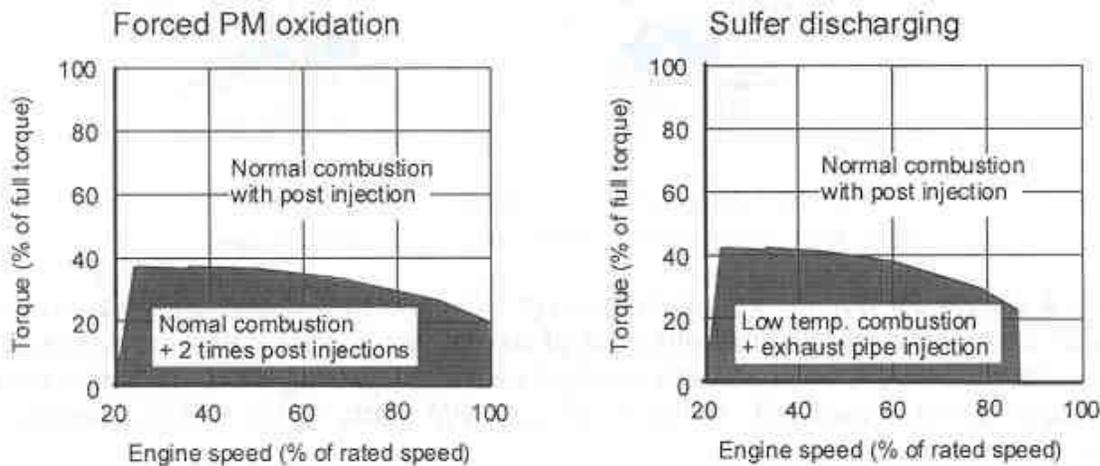
With CDPF in the front, NO<sub>2</sub> can oxidize soot, giving lower back pressure. Back pressure goes up with decreasing NOx due to more LNT regenerations and resultant soot.

## NOx Trap + CDPF

CDPF + LNT + DOC chosen; 1.8% FP

Issues: Keep soot from building up given low NOx target; control regeneration to keep LNT T < 700°C

# A 4.0 liter light duty commercial truck is fit with the DPNR system

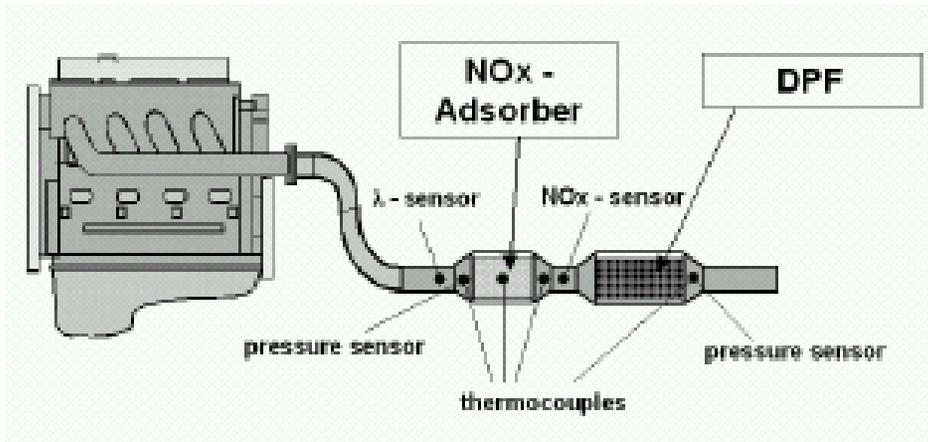


Temperatures from 4l TSI-CR are sufficient to use only auxiliary injections to regenerate filter. Desulfation requires low-temperature combustion control.

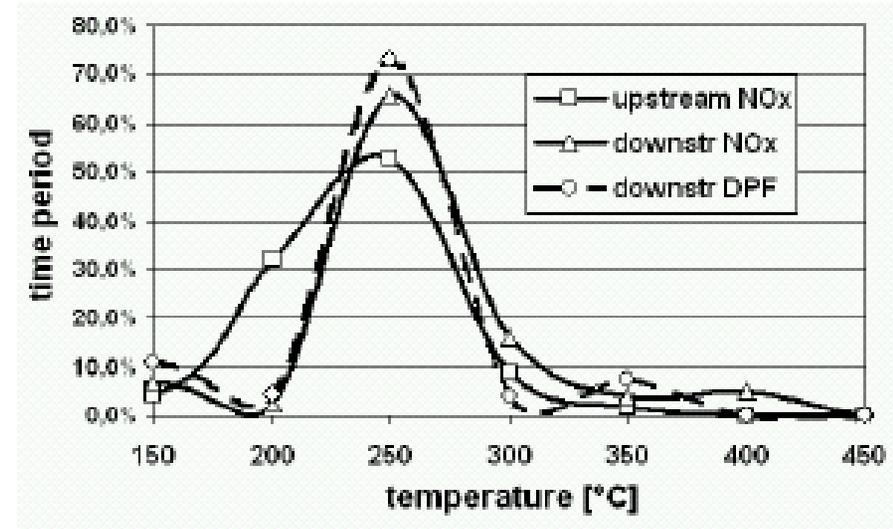
- PM efficiency increases from 90% to 96% after 2000 hrs.
- Ash back pressure increases 30%
- In Japan Transient Cycle, temperatures are too low, necessitating low temperature combustion at low load.

65% NOx aged efficiency.  
 NOx emission more than doubles upon 2000 hrs of aging in 40 ppm sulfur fuel (200,000km);

# LNT / DPF synergies show on LDD



1750 kg vehicle with 2.0 l engine; Ce-FBC, uncat.  
4.6 l DPF



During 660 km of mixed driving, the DPF never exceeded 450°C and was hotter than LNT inlet.

- High LNT exotherms and NO<sub>2</sub> slip may have burned soot.
- Cordierite DPF could work well with LNT
- High cell density LNT might minimize NO<sub>2</sub> slip
- Oil dilution with fuel is a problem: 7.7% over 15,000 km
- 55 to 65% NOx eff. With 4.5 to 5% FP in certification cycle testing

# Exhaust emission control systems are part of the solution

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- DPFs, DOCs, SCR will be applied in 2005 in Japan and Europe
  - some LNT in 2007 in the US
  - LNT in LDD this year
- Filters are in the optimization stage
  - understanding improving regeneration
  - filter properties
  - ash management issues
- NOx solutions are available at +70%
  - SCR is being optimized
  - LNT is on dynos
- Integrated solutions are making HDD the environmental benchmark

# THE END

Thank you.