Diesel Exhaust Emission Control

Tim Johnson

October 8, 2003

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Diesel emission control technology is making significant progress

- General technology approaches to hitting the regulations
- Filter technology
- NOx solutions
- Integrated solutions

Regulations and Approaches

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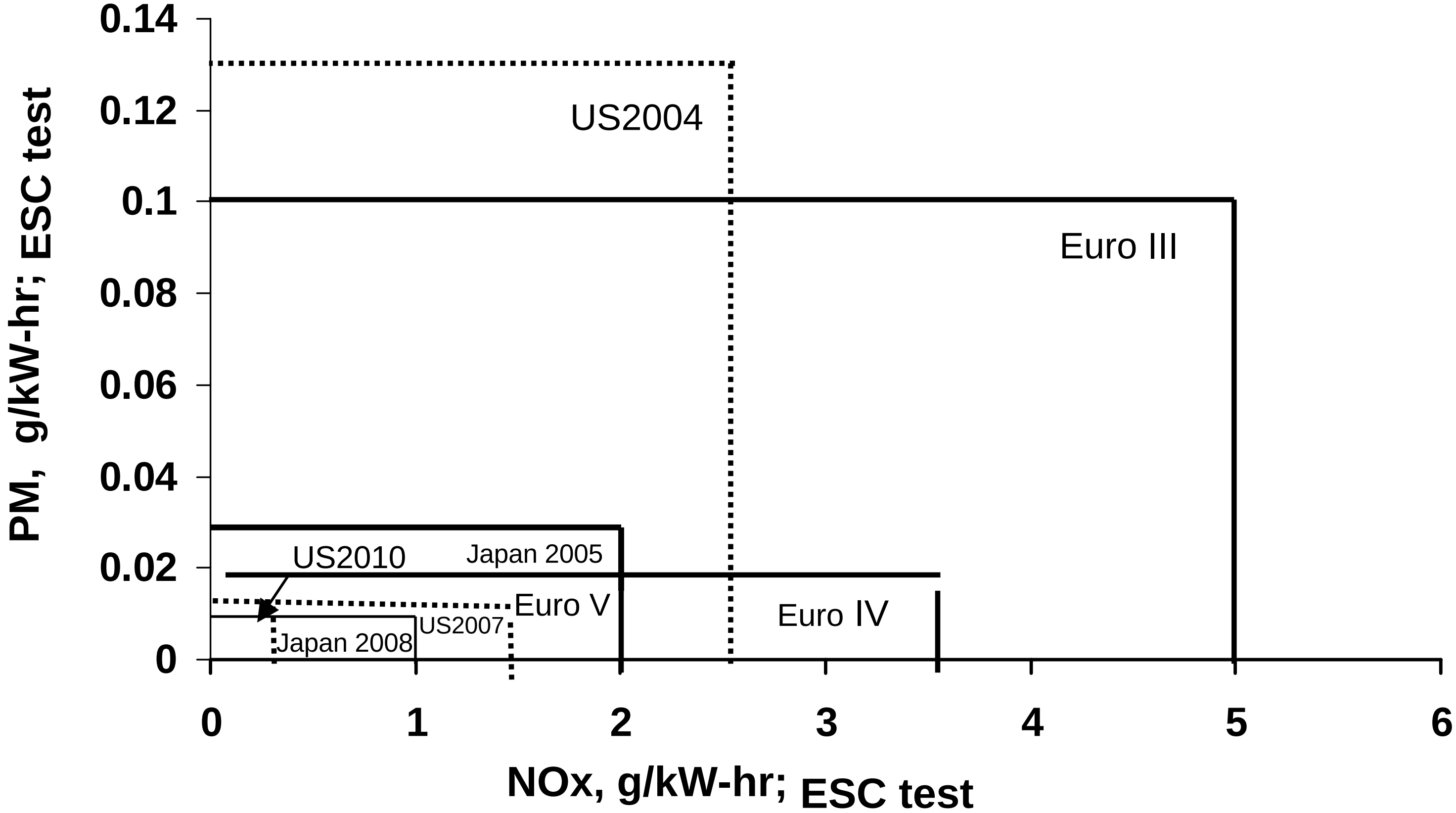
Euro IV and Japan 2005 are coming next, with significant PM and NOx tightening; US2007 goes further; US2010 very low;



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

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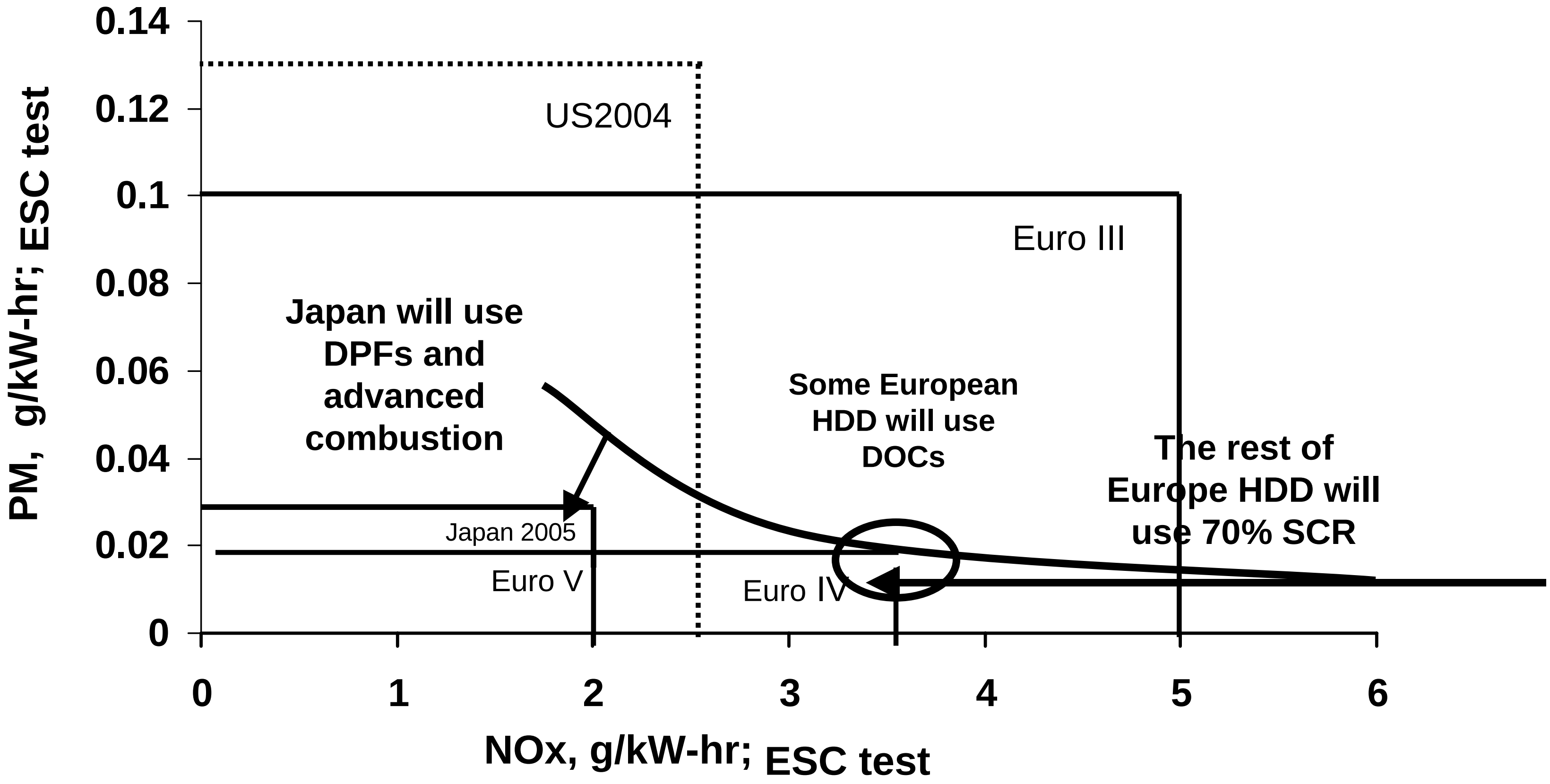
In 2005, filters, DOCs, and SCR will be used



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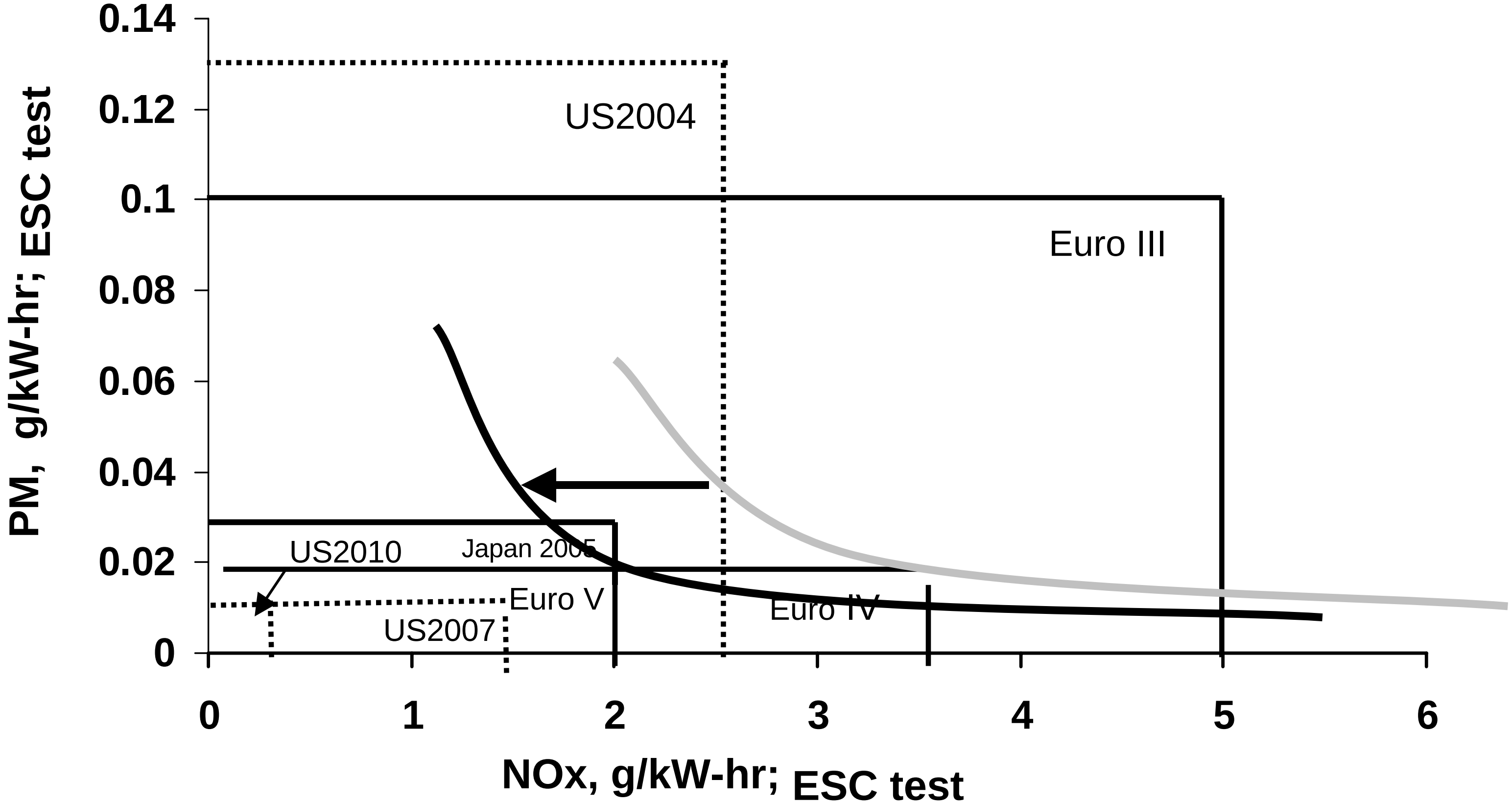
By 2007+, engine technologies are expected to make significant advances



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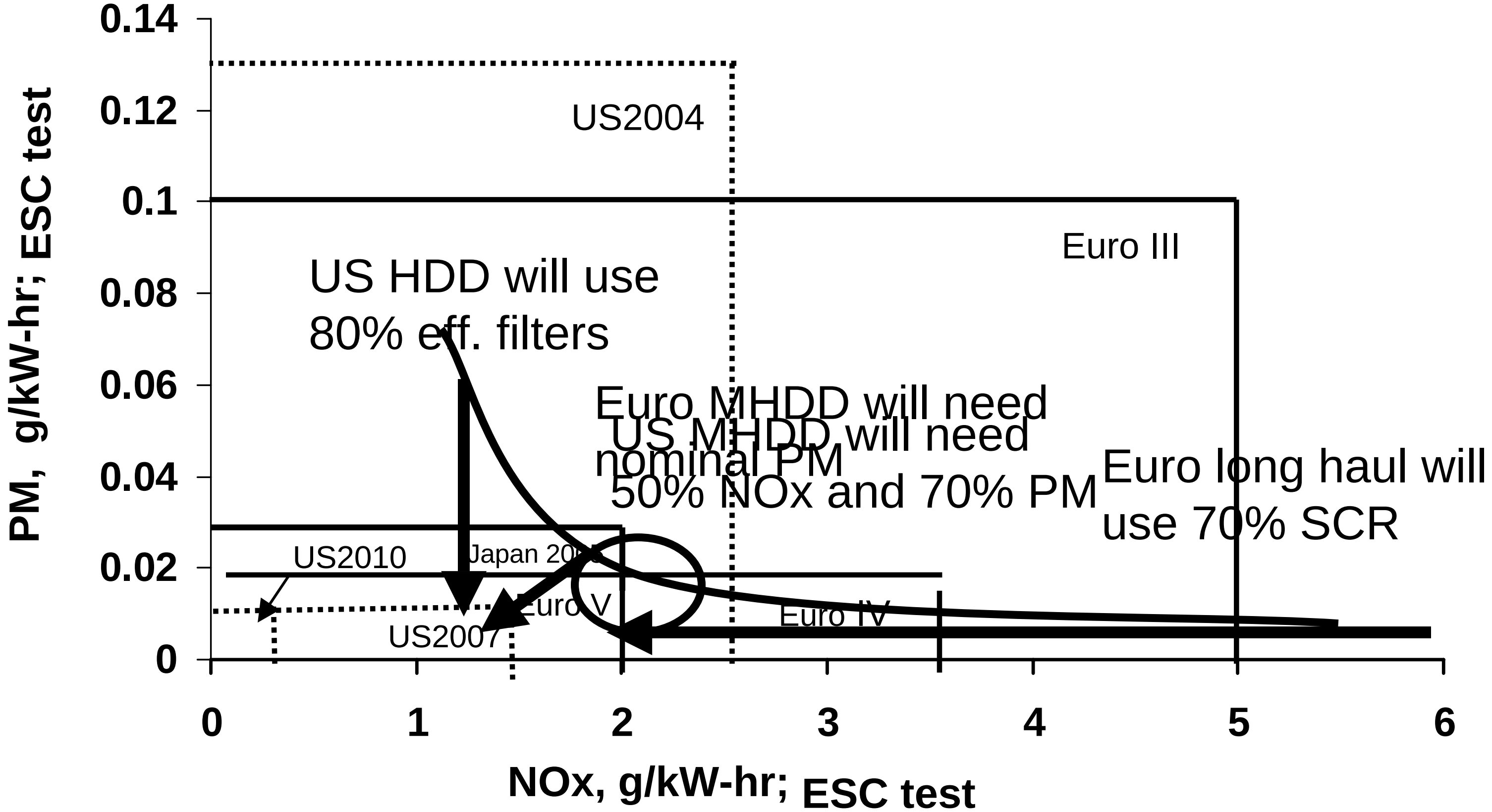

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Recent developments in filters

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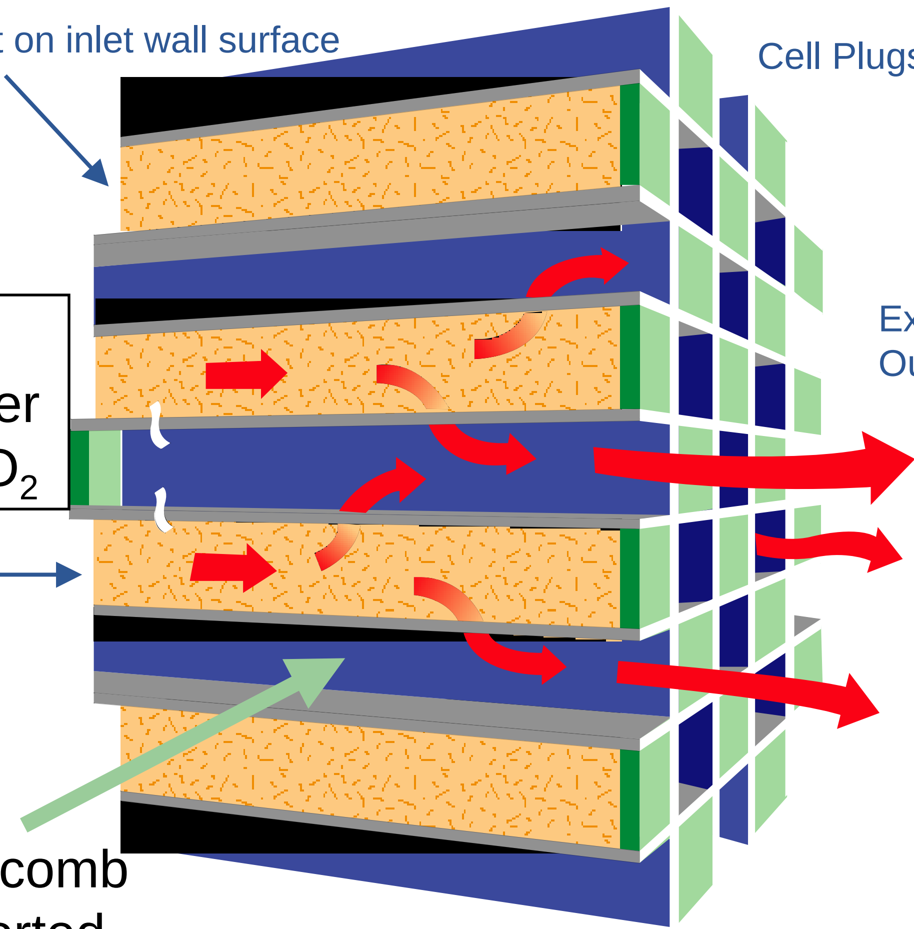
Diesel particulate filters use porous ceramics and catalyst to collect and burn the soot



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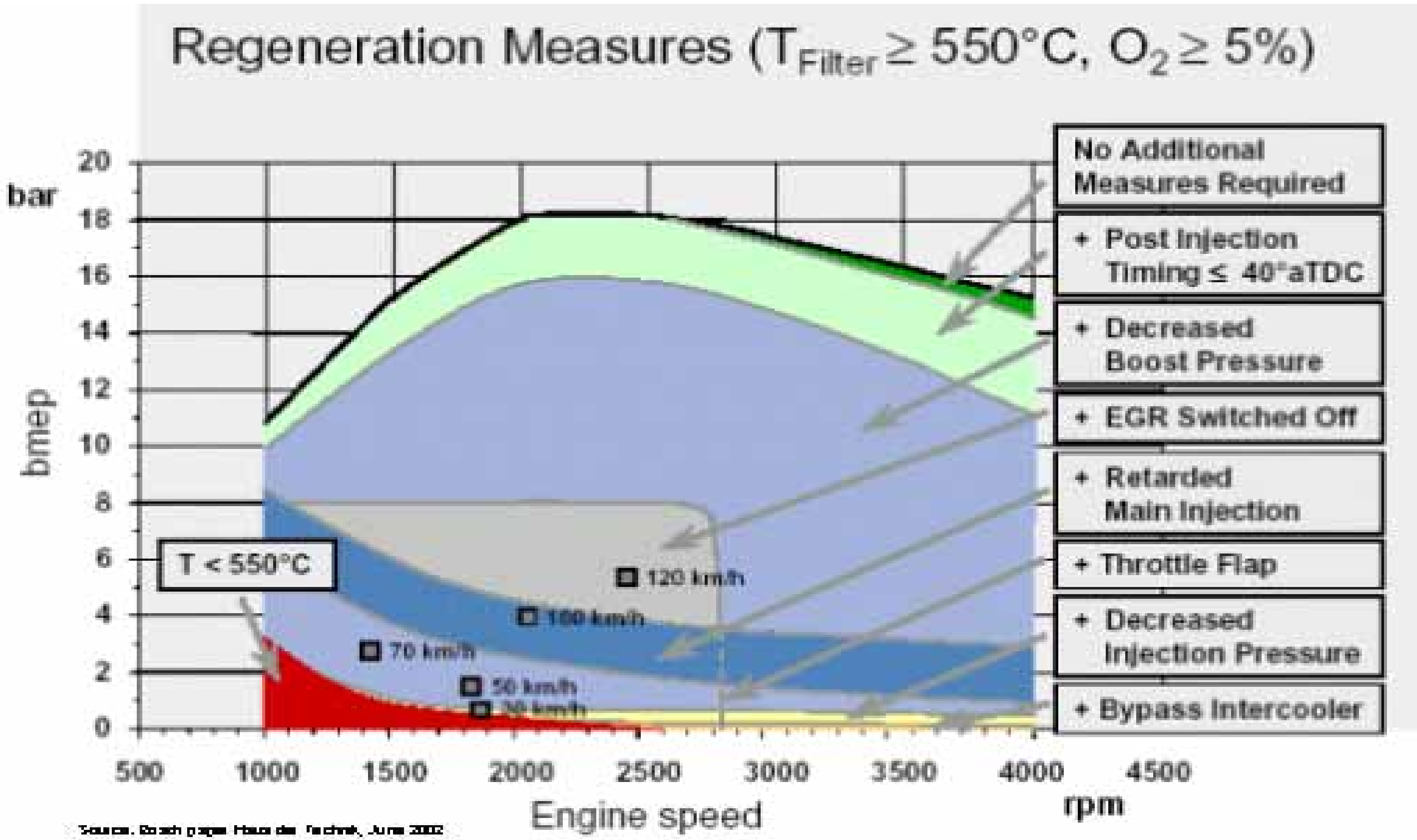
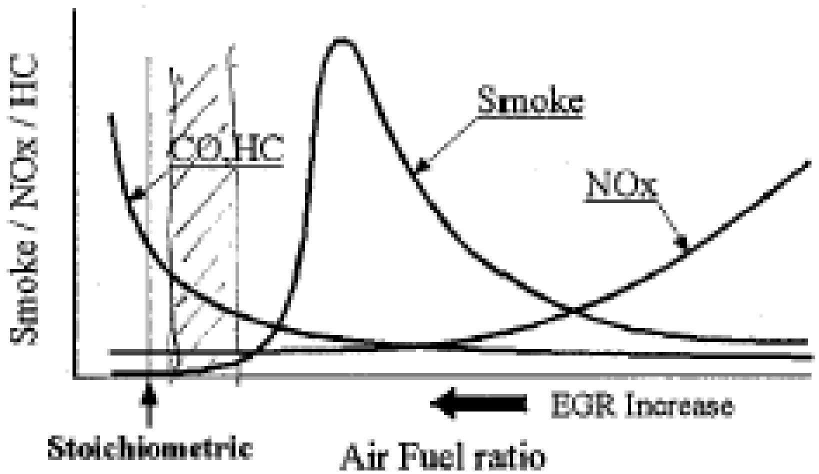
Regeneration strategies are being refined for better reliability

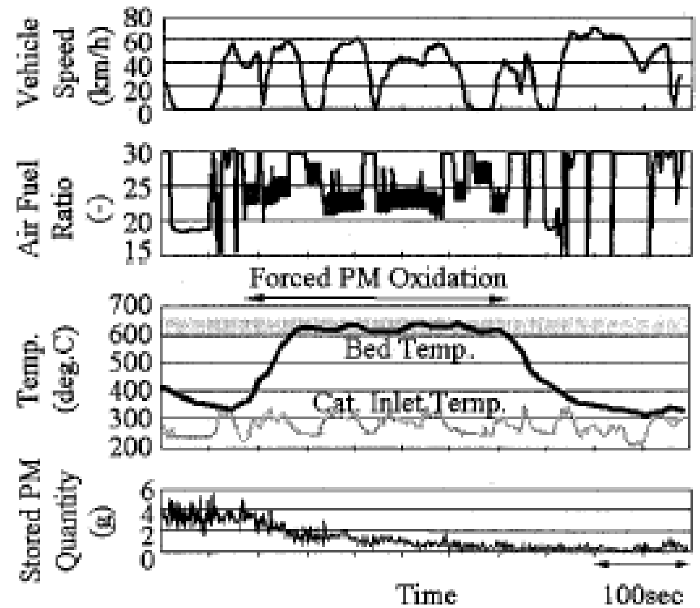


Bosch, Vienna Motorsymposium 4/02

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



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

Toyota, JSAE 5/03

- 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.

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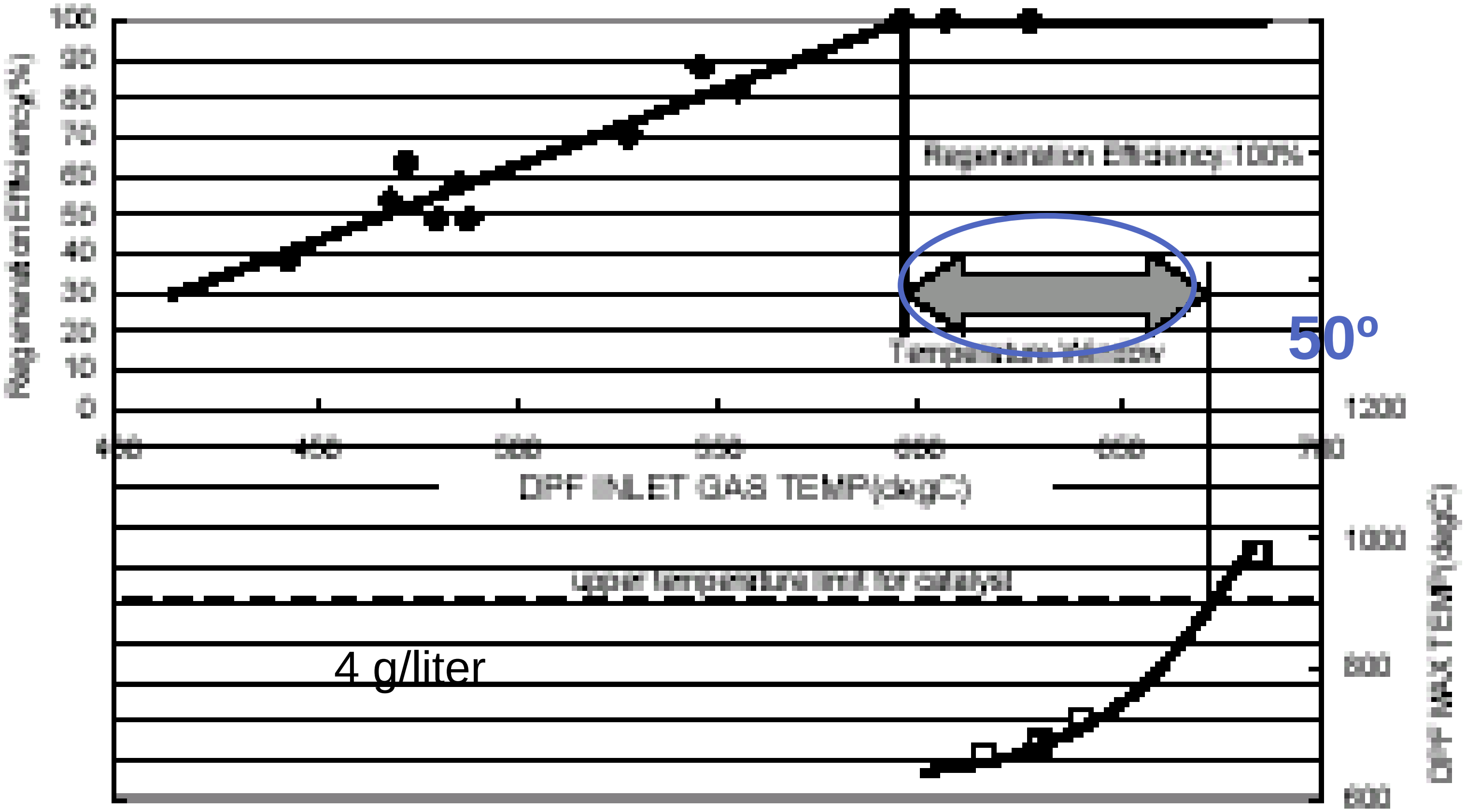
Safe regeneration characteristics of catalyzed SiC filter systems are characterized



NGK 2003-01-0383

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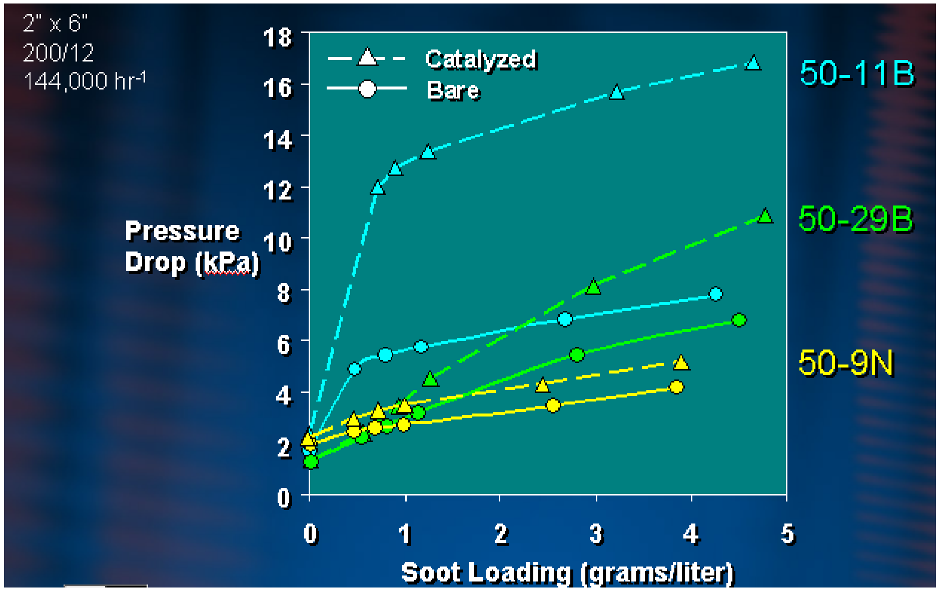
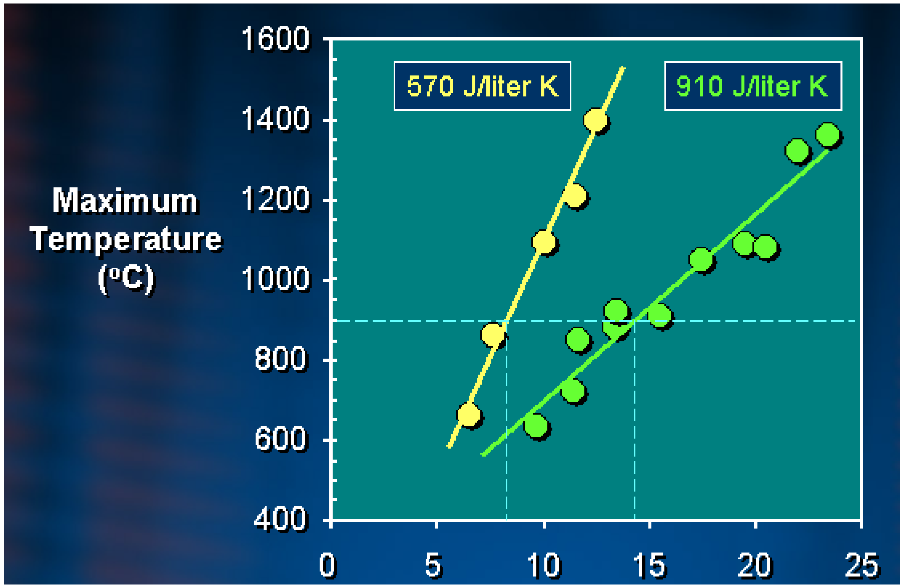
Progress is being made in dropping back pressure and increasing thermal durability



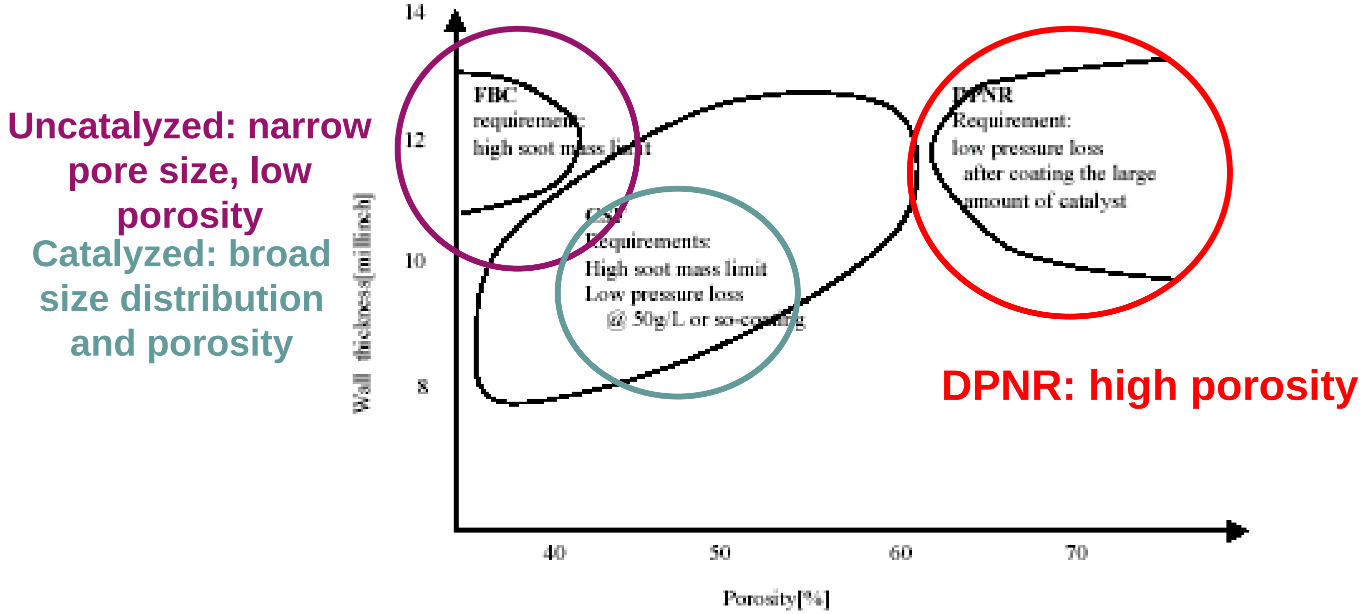


Code: 50-11B means 50% porosity, 11 µm avg. pore size, broad (vs. narrow) pore size distribution

A narrow pore size distribution of small pores gives the lowest pressure drop with or without catalyst.

Soot capacity is increased 75% by increasing thermal mass by 60%.

Pore structure can be engineered for the application



Ibiden SAE 2003-01-0377

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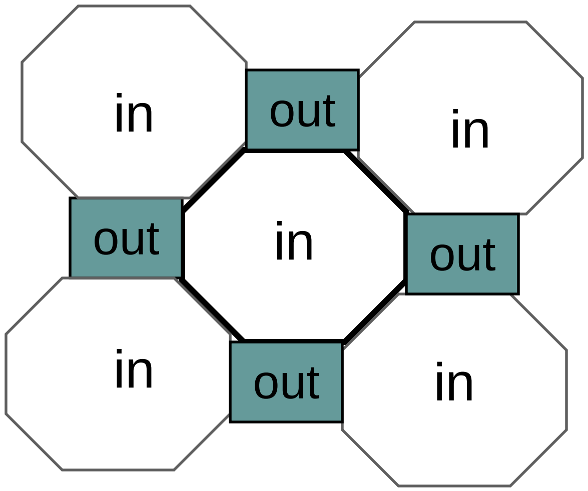
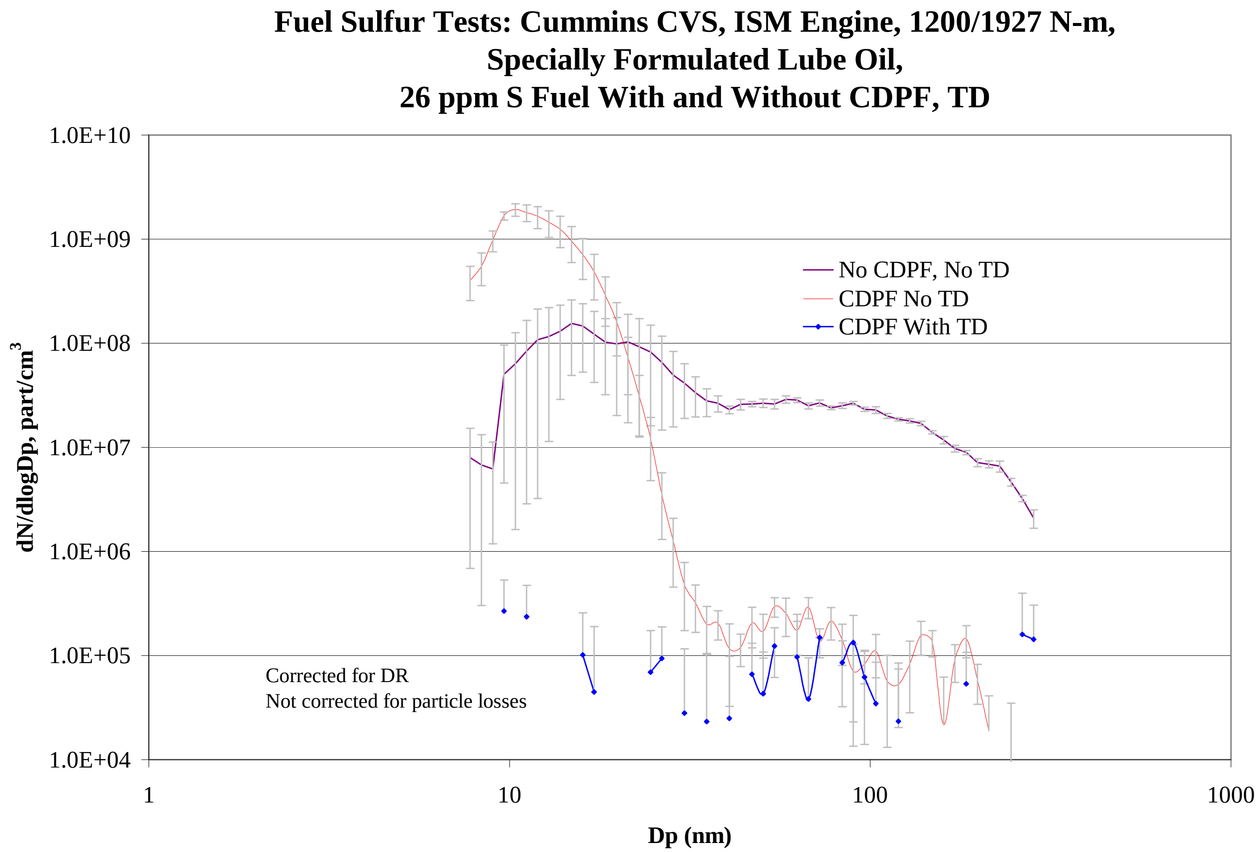
New filter designs are increasing the ash storage capacity of filters



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

(PSA, ETH Particulate Conf. 8-03)

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



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

Univ. of MN, CTA Monterey 3/03

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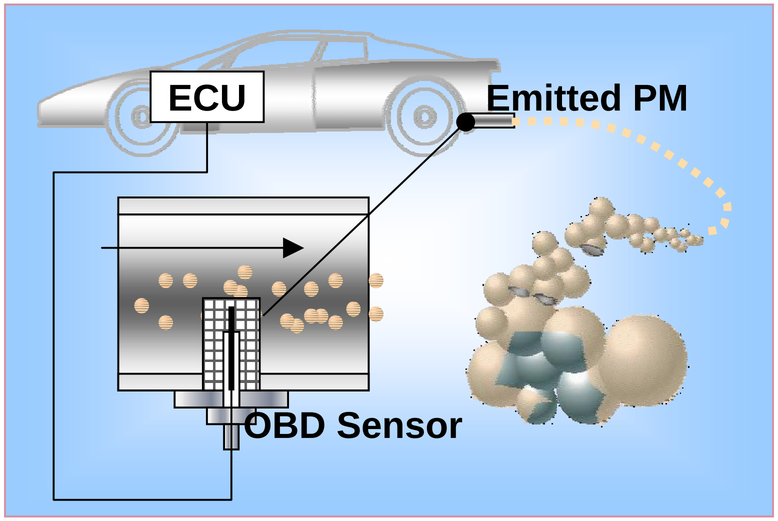
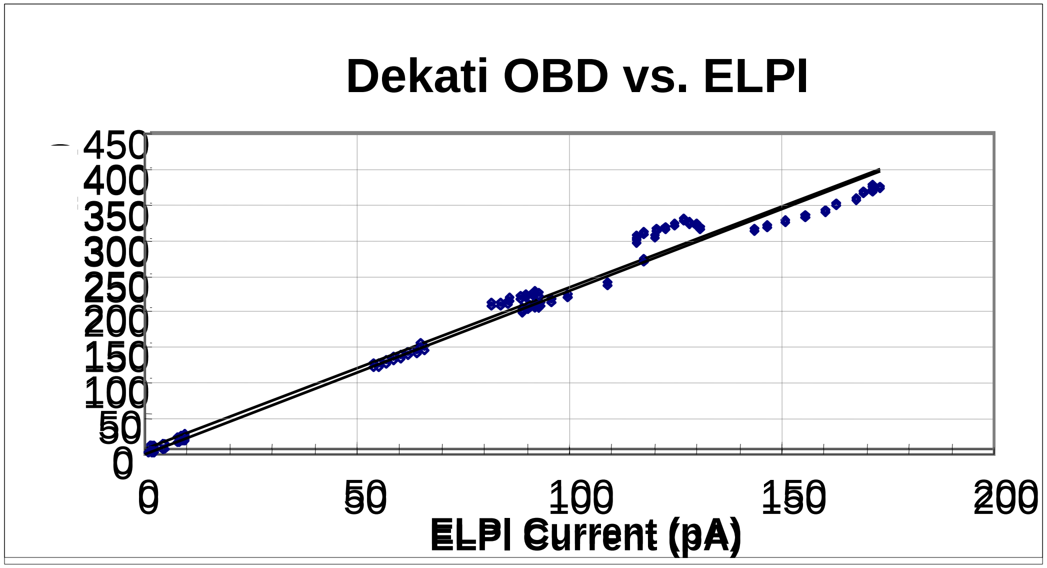
PM OBD sensor is in early stages of development





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

Dekati 8-03

NOx Control

NOx control is difficult in lean conditions

- In stoichiometric conditions (like typical gasoline engines), the three way catalysts takes our 98%+ of the NOx:

$$CO + NOx = CO_2 + N_2$$

- In lean conditions, the CO prefers to react with oxygen:

$$CO + 1/2O_2 = CO_2$$

- Emission control systems need to accommodate

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State-of-the Art SCR system has NO_2 generation and oxidation catalyst to eliminate ammonia slip

SCR Catalyst (S)

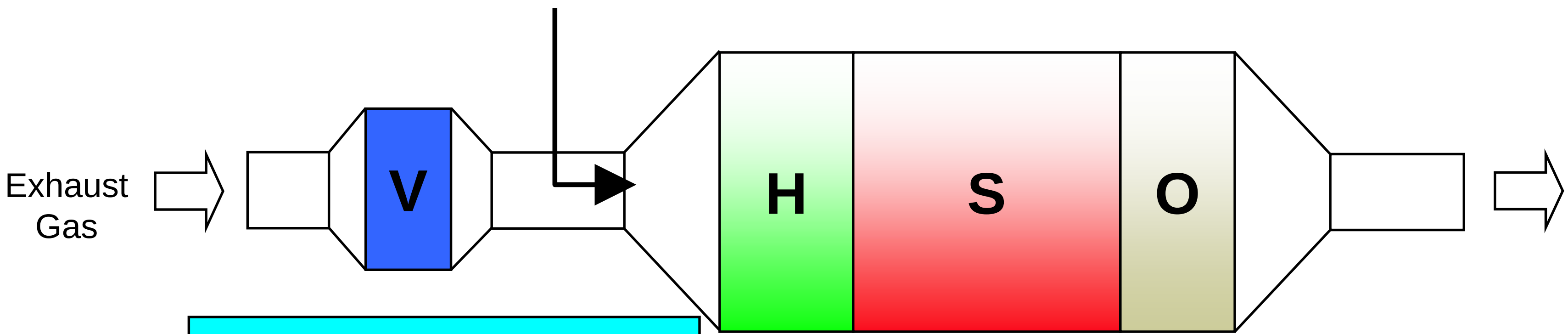
$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$

$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$

$8NH_3 + 6NO_2 \rightarrow 7N_2 + 12H_2O$

Urea

$(NH_2)_2CO$



Oxidation Catalyst (V)

$2NO + O_2 \rightarrow 2NO_2$

$4HC + 3O_2 \rightarrow 2CO_2 + 2H_2O$

$2CO + O_2 \rightarrow 2CO_2$

Oxidation Catalyst (O)

$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$

Hydrolysis Catalyst (H)

$(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2$

Degussa, 9-99

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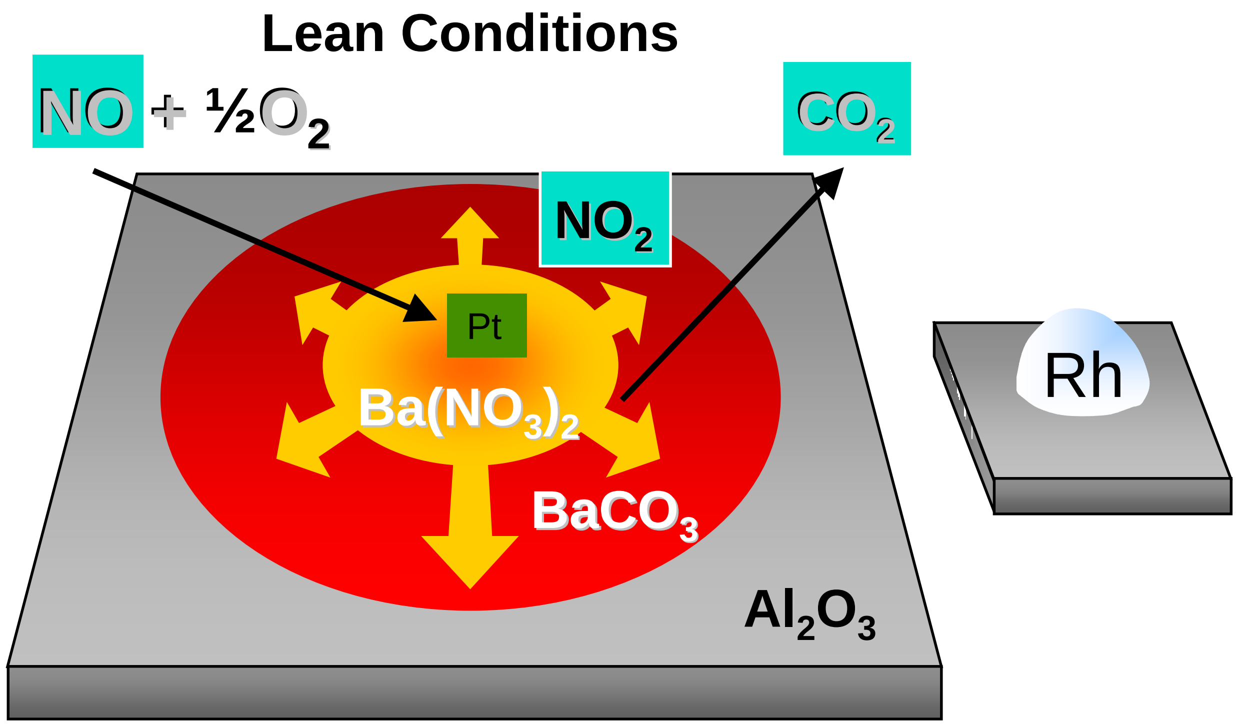
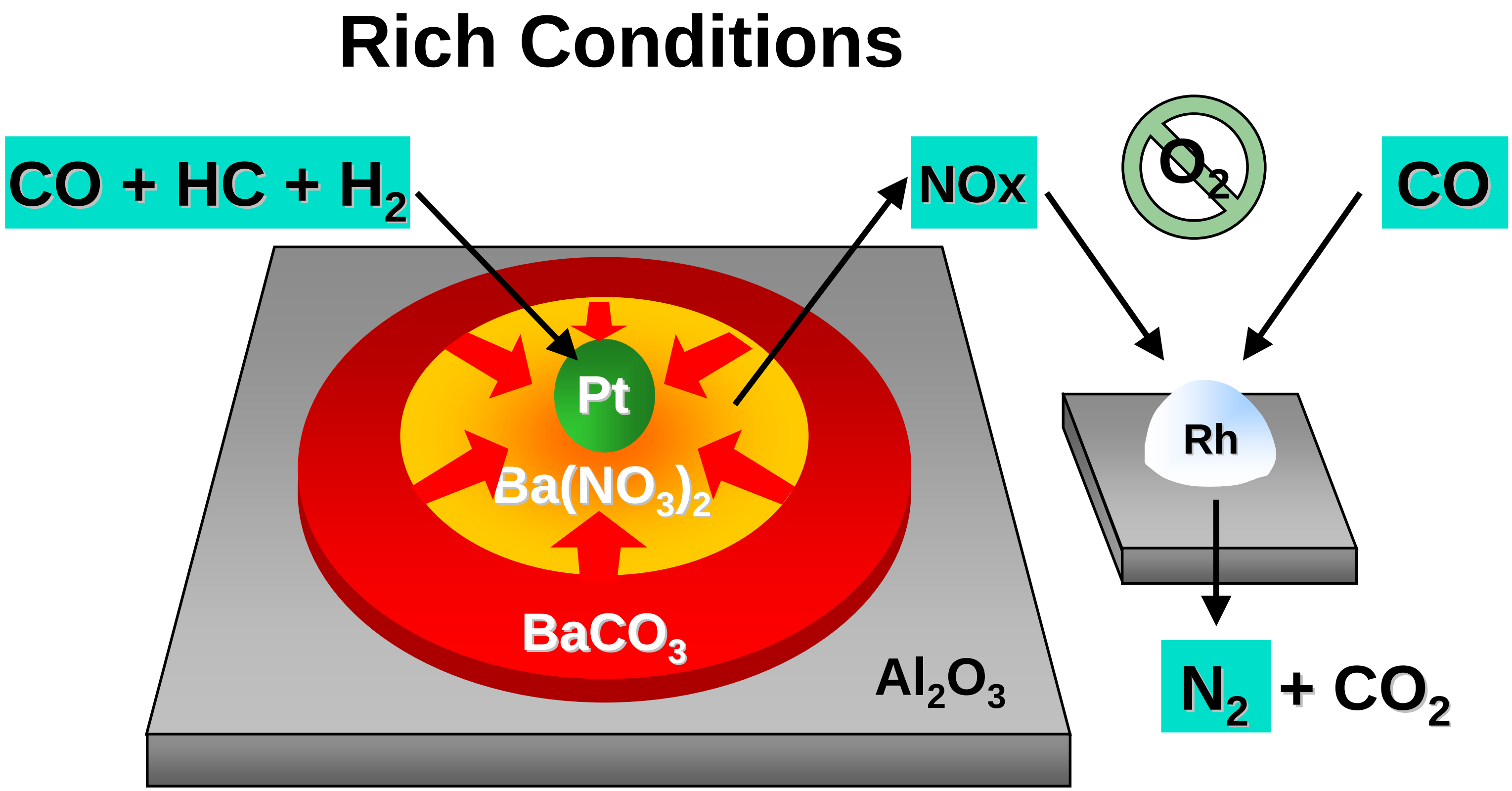
The NOx adsorber in storage mode during lean conditions; NOx stored as a nitrate



$$2NO_2 + BaO + 1/2O_2 = Ba(NO_3)_2$$

In rich mode, the nitrate dissociates to NO2, which is converted to nitrogen using the HCs or CO



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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%	3-4% urea or about **2%** 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; PGM cost issues
DeNOx catalyst	20-60%	2 to 6%	0.85 to 4	Generally not sensitive to sulfur; HC slip issues; durability needs proving

SCR

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77% of diesel is pumped at 2200 stations

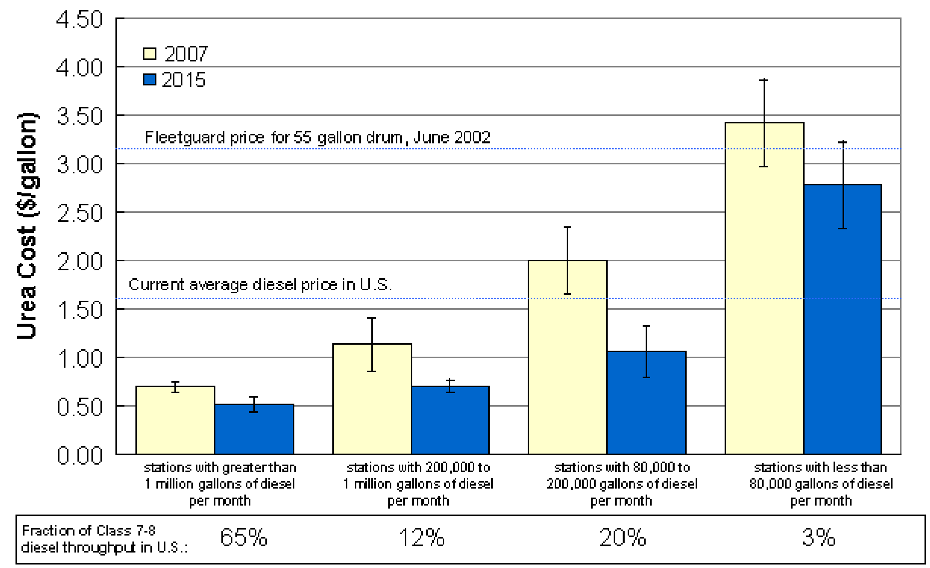
Profiles of Fueling Stations Serving the Class 7 & 8 Truck Market

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

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

Estimates are that about 50% of 2007 trucks would need SCR to make infrastructure viable

Retail Urea Cost By Diesel Station Throughput



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

EMA study by Tiax 6-03

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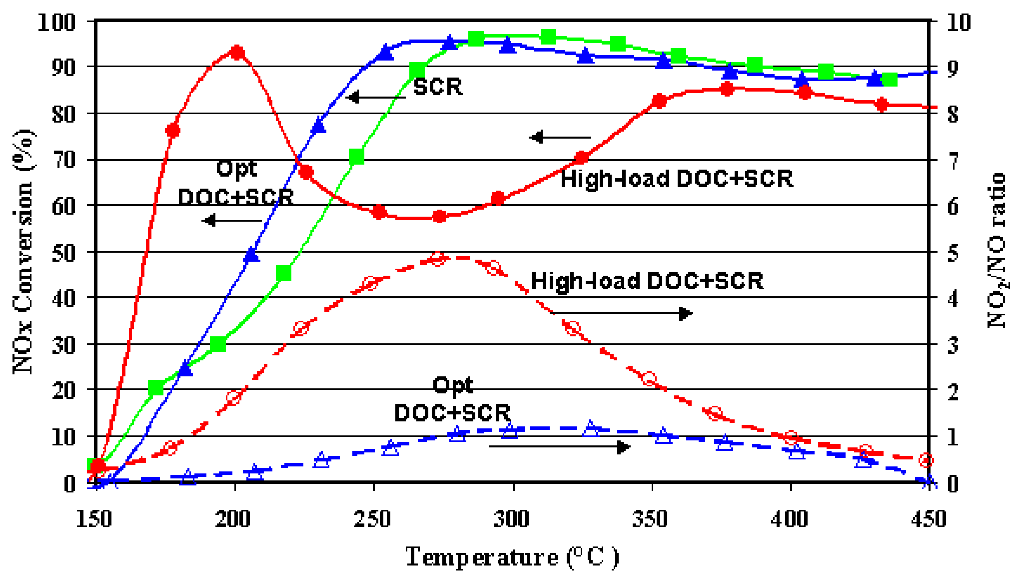
NO2/NO ratio is important in achieving good low temperature SCR performance



$4\ NH_3 + 4\ NO + O_2 \longrightarrow 4\ N_2 + 6\ H_2O$ (1)

$2\ NH_3 + NO + NO_2 \longrightarrow 2\ N_2 + 3\ H_2O$ (2)

$8\ NH_3 + 6\ NO_2 \longrightarrow 7\ N_2 + 12\ H_2O$ (3)

- Reaction 1 is fast, Reaction 2 is very fast, Reaction 3 is very slow
  - low temperature SCR is strongly promoted by NO_2
  - but too much NO_2 can cause problems

Johnson Matthey DEER 8-03

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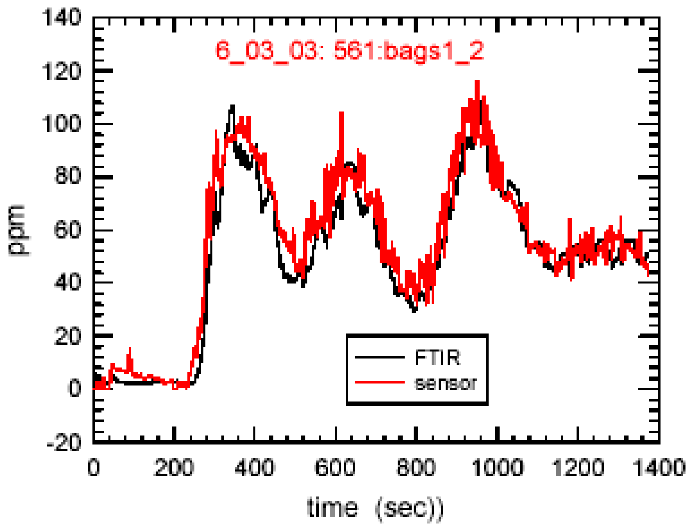
Ammonia sensor is in development

Vehicle test:
Comparison of NH_3 measured at the tailpipe using FTIR with that predicted by the sensor (after compensating for water)



Lean NOx Traps

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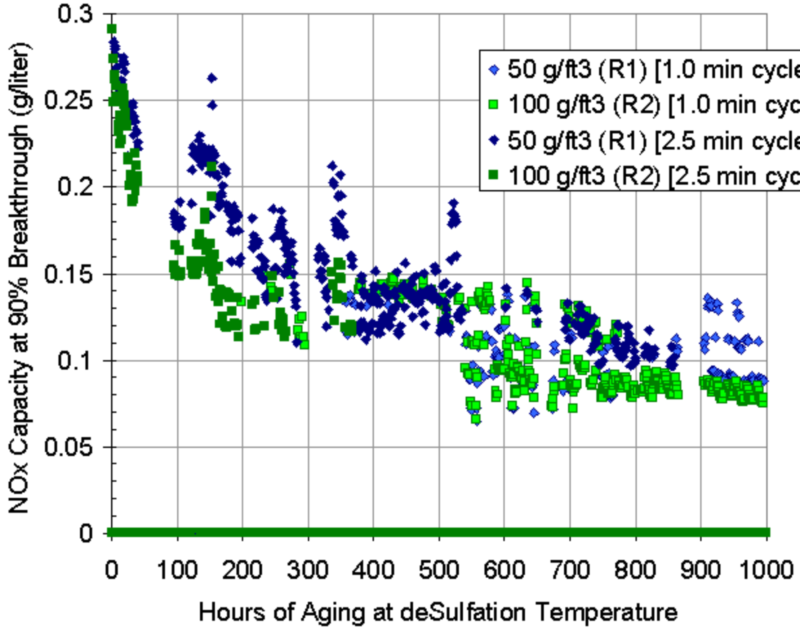
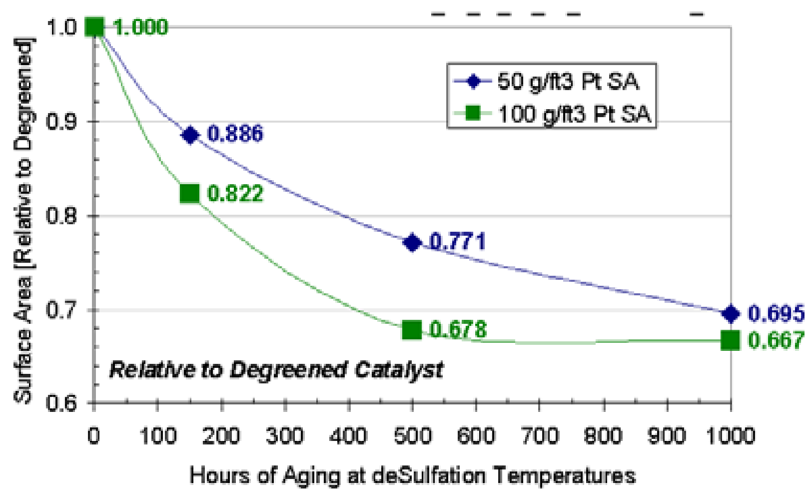
LNT aging studies are expanded to 1,000,000 effective miles; step deterioration observed at 600,000 miles





Aging generally follows loss in active surface area, but phosphorous and zinc contamination also evident

LNT formulation shows initial decline in capacity, and then stabilization out to 600 hours (est. 600,000 miles) before declining again

- **SV = 21,000/hr ; standard lube oil**
- **Accelerated Test Cycle:**
  - A: 36 Minutes @ 350ºC with S Loading and Red-Ox Cycling
  - B: 63 Minutes @ 500ºC with Red-Ox Cycling
    - 6.3 Minutes of Rich Operation for deSulfation
  - A-B-A-B-A-B Sequence Repeated 1,000 Times

Emerachem DEER 8-03

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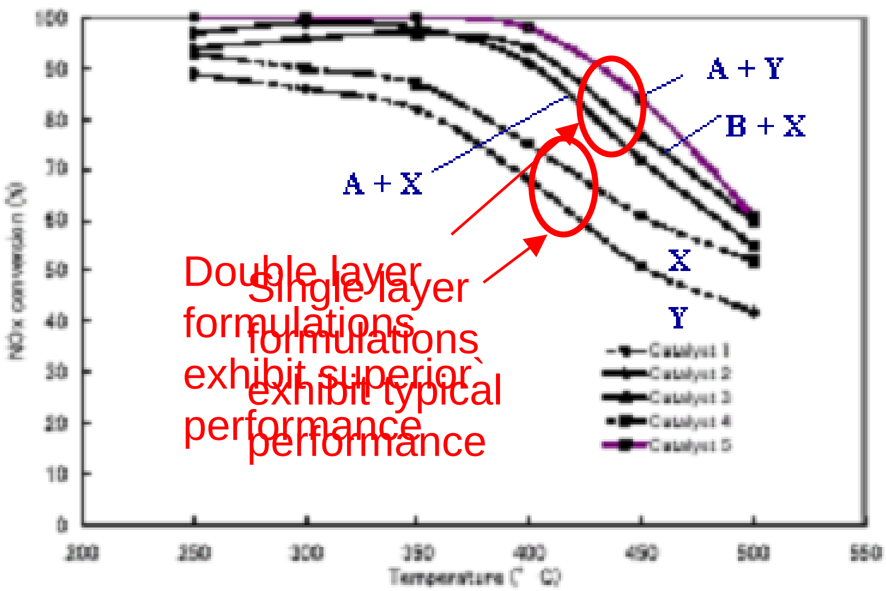
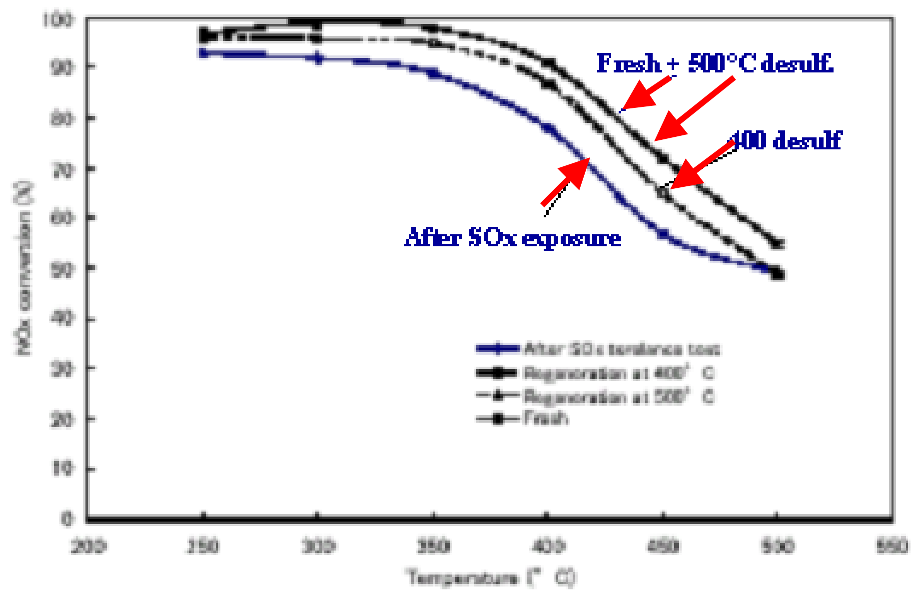
A new double-layer LNT is developed that keeps SOx off the adsorbing material





Top layer adsorbs SO_2 for moderate storage capacity, but quick release.

VTT, Mitsubishi SAE 2003-01-1158

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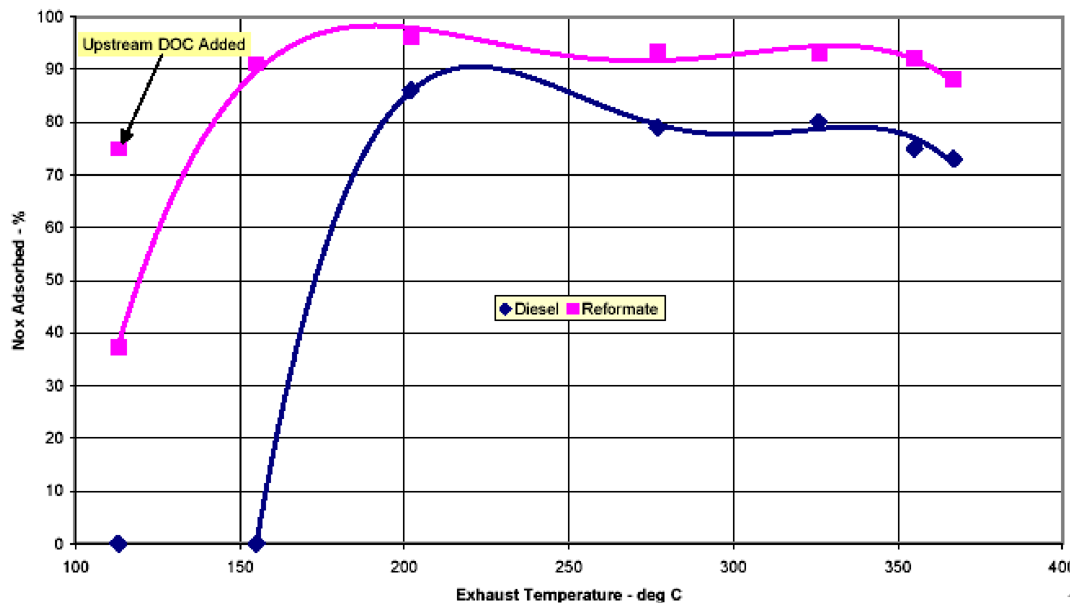
Hydrogen/CO reformate significantly improves LNT performance

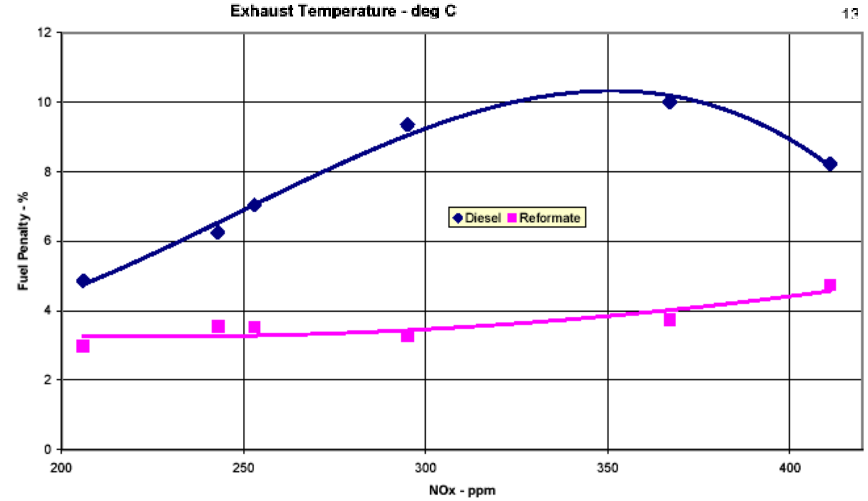
Electric power	W	250
O/C		1.1
Diesel flow rate	g/s	0.8
Corresponding chemical power	kW	35

Concentration (vol %)	
H2	8.2
O2	1.4
N2	68.7
CH4	2.6
CO	14.3
CO2	4.7
C2H4	2.4
C2H2	0.0

Energy efficiency to hydrogen, CO and light HC	70%
Soot (opacity meter)	0



Hydrogen facilitates the desulfation step and is very efficient in regenerating LNTs



Integrated systems

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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%

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

Ceramics LLT, SAE 2003-01-0774

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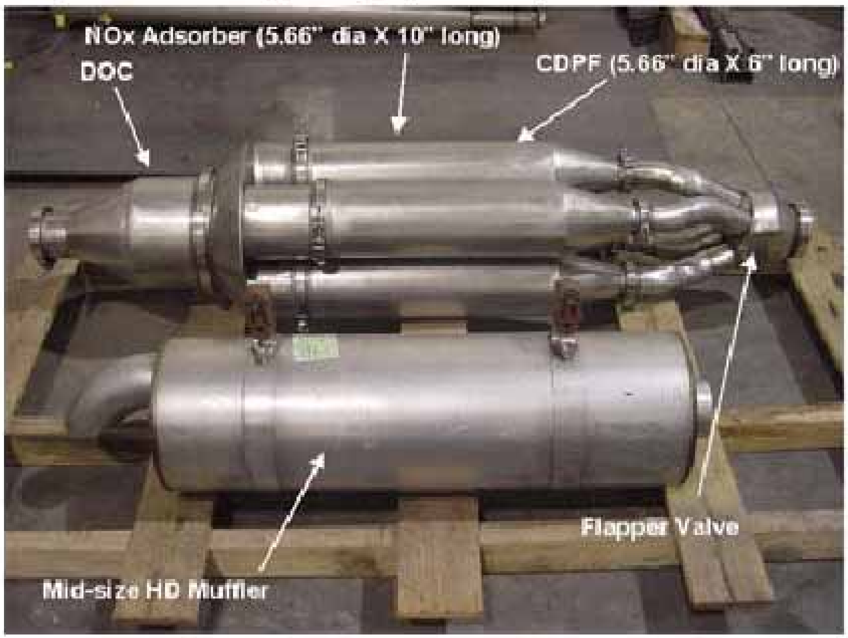
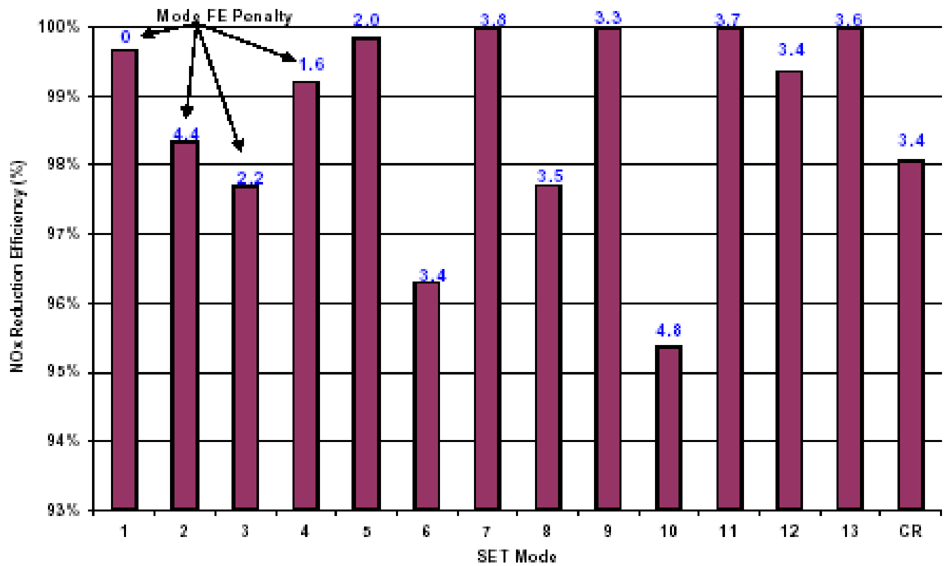
The large EPA 2-leg LNT/DPF system is replaced with a more "efficient" 4-leg system



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



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

EPA Non-road NPRM 4-03

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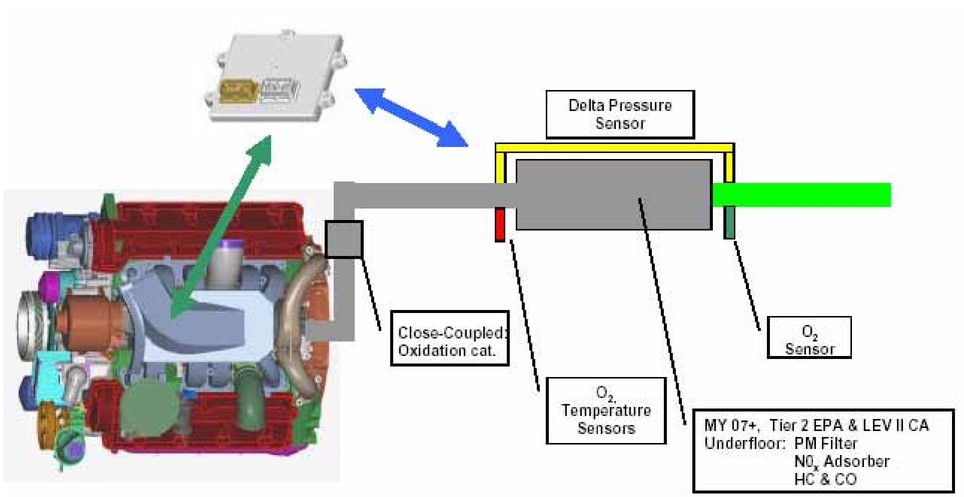
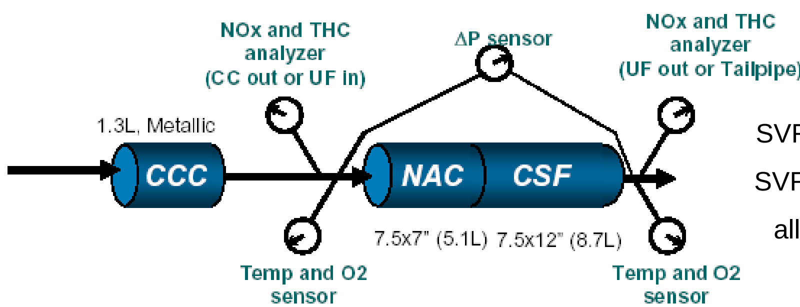
LDT is hitting Bin 5 with LNT+CSF combination



Condition	Engine Out	Combustion Condition
NO_x Regen	Rich	Thermal Management + Pilot + Main Injection
Soot Regen	Lean	Thermal Management + Pilot + Main + Post
Sulfur Regen	Rich	Thermal Management + Pilot + Main + Post



SVR LNT = 1.2

SVR DPF = 2.0

all cordierite

Test	CO [g/mi]	CO2 [g/mi]	NOx [g/mi]	NMHC [g/mi]	FE [mpg]	PM [g/mi]
FTP-75 FUL limits	4.2	-	0.07	0.090	-	0.01
FTP-75	0.399	480.27	0.033	0.089	21.12	0.006
FTP-75	0.367	491.67	0.038	0.056	20.32	-
bag 1	0.971	547.87	0.141	0.222	18.47	0.008
	1.051	583.44	0.181	0.269	17.08	-
bag 2	0.272	475.03	0.003	0.057	21.37	0.004
	0.200	475.27	0.000	0.000	21.04	-
bag 3	0.207	439.17	0.009	0.049	23.11	0.007
	0.166	453.40	0.003	0.000	22.05	-

Start
+1600 mi

	City, mpg*	Highway, mpg*	Combined, mpg*	Combined gal/mi	CO_2
Dodge Durango					
- Gasoline	12	17	13.8	0.072	
- Diesel	20.3	25.0	22.1	0.045	
			+60% Improve	37% Reduction	27% Reduction
Dodge Ram 1500					
- Gasoline	12	16	13.5	0.074	
- Diesel	19.8	24.6	21.7	0.046	
			+61% Improve	38% Reduction	

Cummins, DEER 8-03

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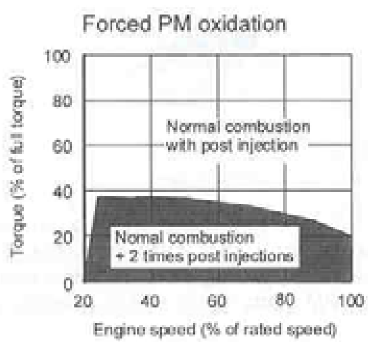
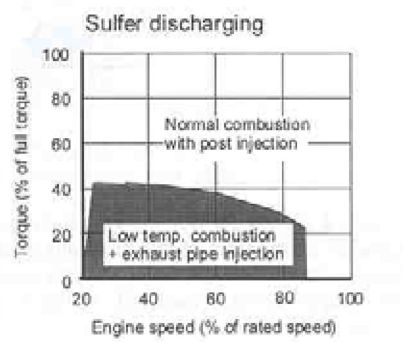
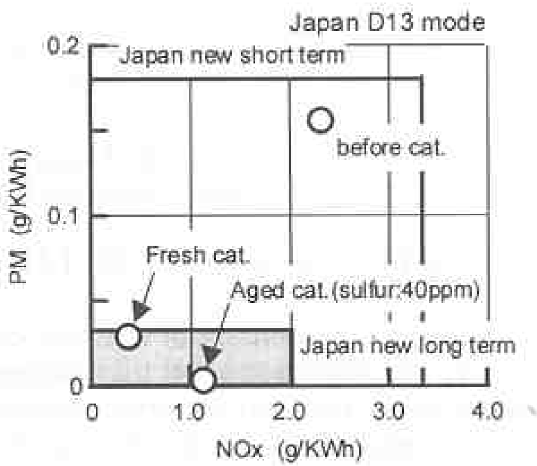
A 4.0 liter light duty commercial truck is fit with the DPNR system





Temperatures from 4l TSI-CR are sufficient to use only auxiliary injections to regenerate and desulfate. Other applications require low-temperature combustion control.



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

- **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.**

Toyota, Vienna Motorsymposium 5/03

Exhaust emission control systems are part of the solution

- DPFs, DOCs, SCR will be applied in 2005 in Japan and Europe
  - DPF and SCR in 2007 in the US
  - LNT in LDD and MDD 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.

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