Developing Trends - Diesel Emission Control Update

Tim Johnson

DEER 2001

August 7, 2001

CORNING

Discovering Beyond Imagination

Outline

- Regulatory Perspectives
  - LDD regs not forcing technology, but HDD regs are
    - LDD filtration technology (Europe) is driven by “green marketing”
    - HDD regs are driving NOx
- Nature of Diesel PM
  - emphasis has shifted to duplicating exhaust plume size distributions
- Filtration
  - Filter materials knowledge and system designs are advancing
- NOx Solutions - HDD
  - Europe is heading to SCR
  - NOx adsorbers developing fast
- Integrated Systems
  - Integrated NOx/PM systems may perform better than filter-only systems
- US LDD trucks look promising

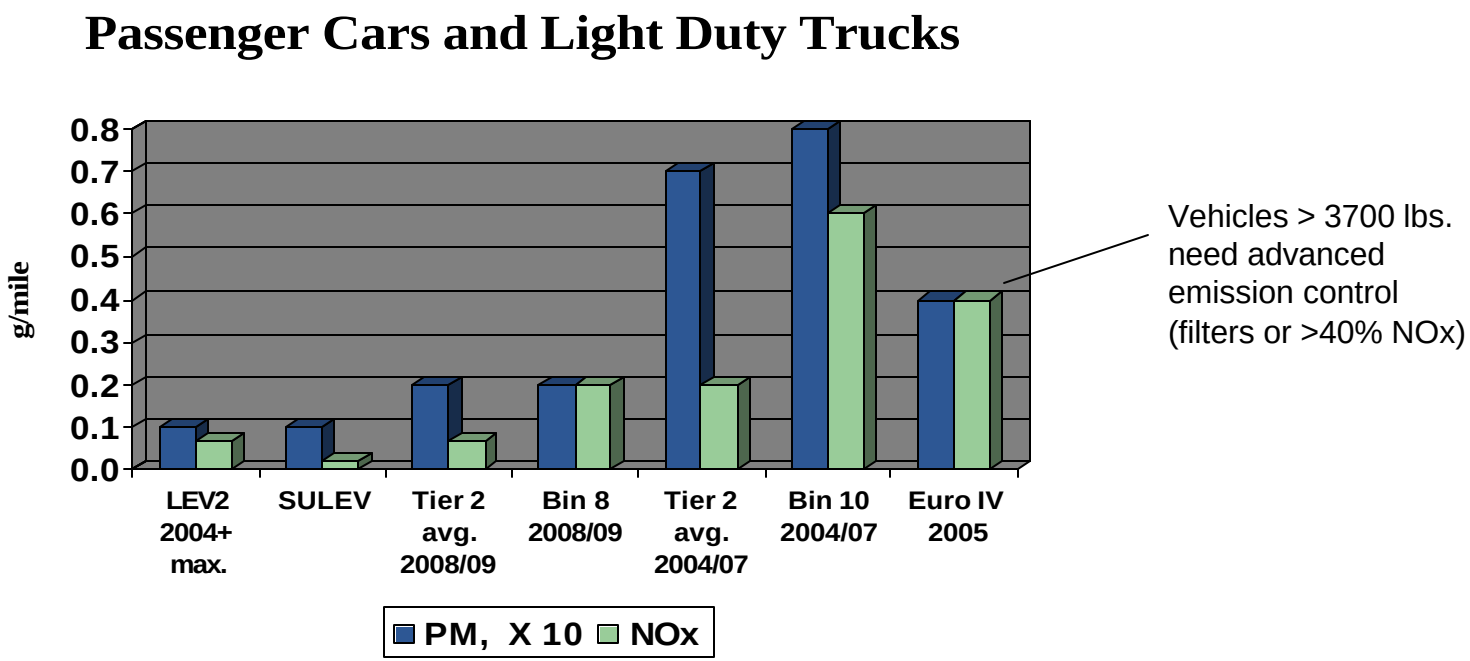
Introduction - Regulatory Perspectives

- US2007 Rule seems solid, but action could occur with the NPRA court case
- Heavier LDD are required to have advanced emission control in Europe, all will practically need NOx control in the US in 2008+
- HDD: Advanced PM <u>or</u> NOx will be needed for Euro IV and V; 50%+ NOx <u>and</u> 70%+ PM will be needed for US2007

CORNING
Discovering Beyond Imagination

LDD regs:

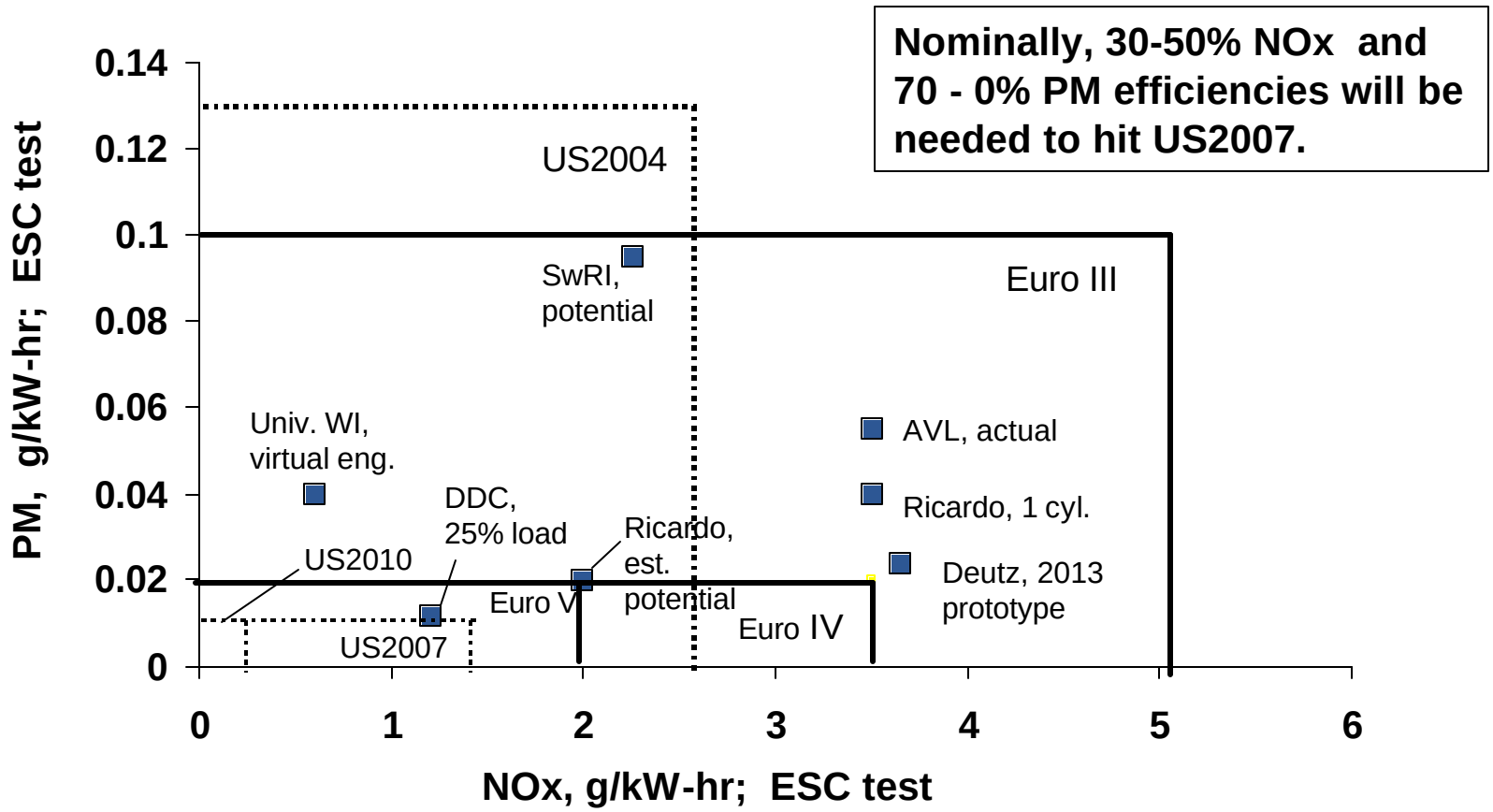
Only heavier PC in Europe will need advanced technology; US has provisions, but “price” is steep; California is very tight



<u>Tier 2 is NOx based</u>. Diesel LDT will likely certify to looser bins, requiring low-NOx offsets to hit the fleet average. What is the prognosis for LDD filters? Green marketing in 2004-07 will require them. 2008+ regs will require them.

- In 2004-07 for every Bin 10 diesel LDT sold, three Bin 5 LDTs will have to be sold
- In 2009, for every Bin 8 diesel LDT sold, 2.6 SULEVs (Bin 2) LDTs must be sold to hit fleet average
- California LEV2 is a maximum emission level and equal to the EPA fleet average NOx requirement

Where will HDD engines be in 5 to 7 years?



•Prototype Engines have cooled EGR, combustion optimization, fully flexible fuel injection, staged turbocharging, multi-hole injectors, high pressure injection.

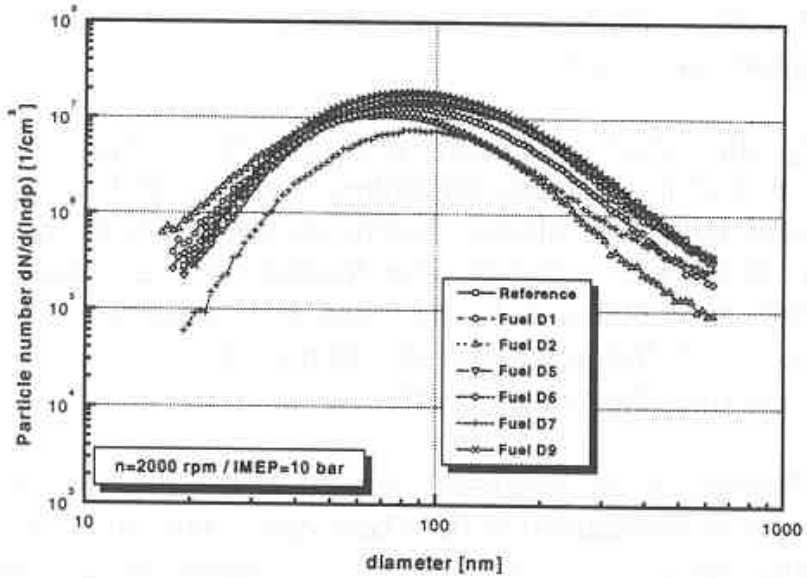
CORNING

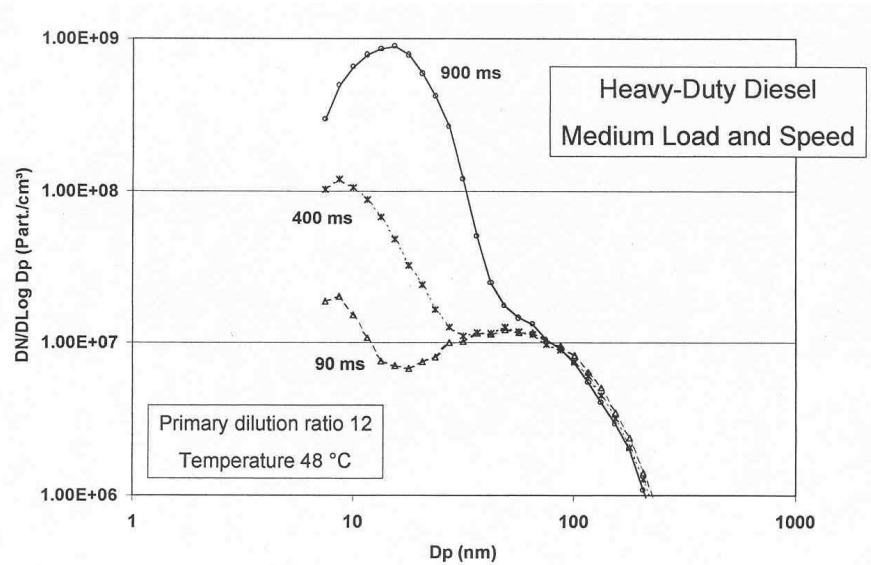
Nature of Diesel PM

- Carbon soot is consistent and easily characterized
- Aerosol nanoparticles are elusive and variable
- Exhaust plumes show aerosols are 1.5 orders of magnitude greater in number

CORNING
Discovering Beyond Imagination

Carbon soot is formed in combustion, and is consistent; aerosol PM is formed on cooling and varies depending on conditions





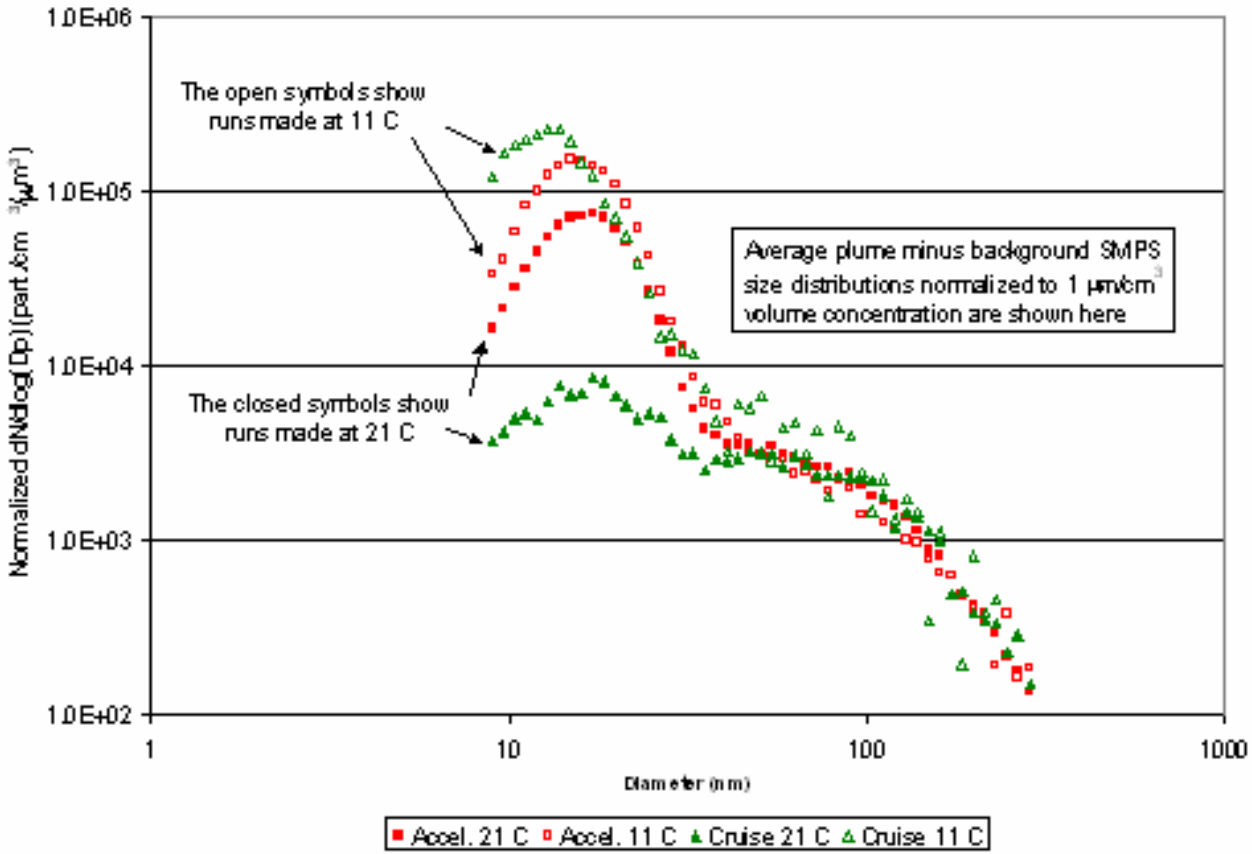
The size distribution of the carbon soot changes little with fuel or other conditions. Samples from combustion chamber extracted using heated lines, high dilution ratio; analyses are for carbon soot only.

Nano-particles are aerosols of <u>sulfuric acid and HCs</u>. Concentrations depend on time, temperature, and dilution ratio, or <u>any factor affecting condensation.</u>

FEV SAE 2000-01-1999

Kittelson, University of MN, EPA MSTRS, July 1999

Nanoparticles can be measured in diesel exhaust plumes on the track

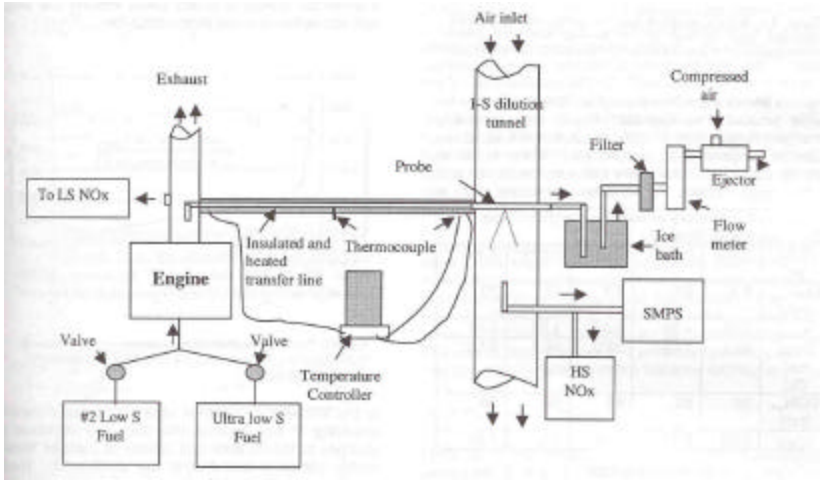


From a mobile PM laboratory following a heavy-duty diesel on the highway. 1999 Cummins engine, California fuel

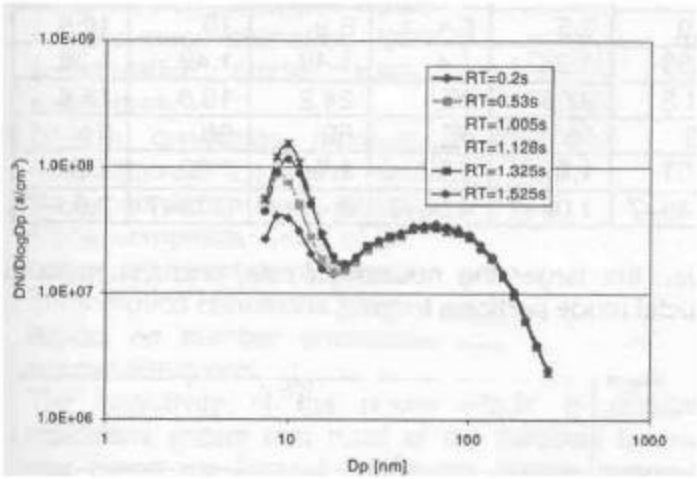
Univ. of Minn. SAE 2000-01-2212

CORNING

Task now is to duplicate the exhaust plume conditions in the laboratory

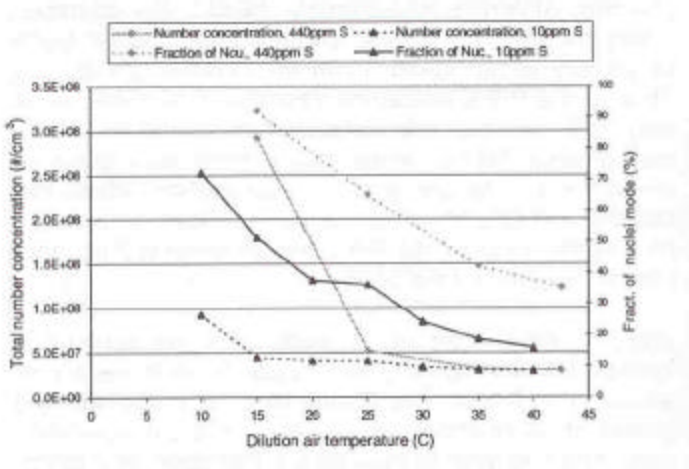


Rapid 1000:1 dilution occurs in one step



Results show stabilization of aerosol particle growth after about 1.1 seconds.

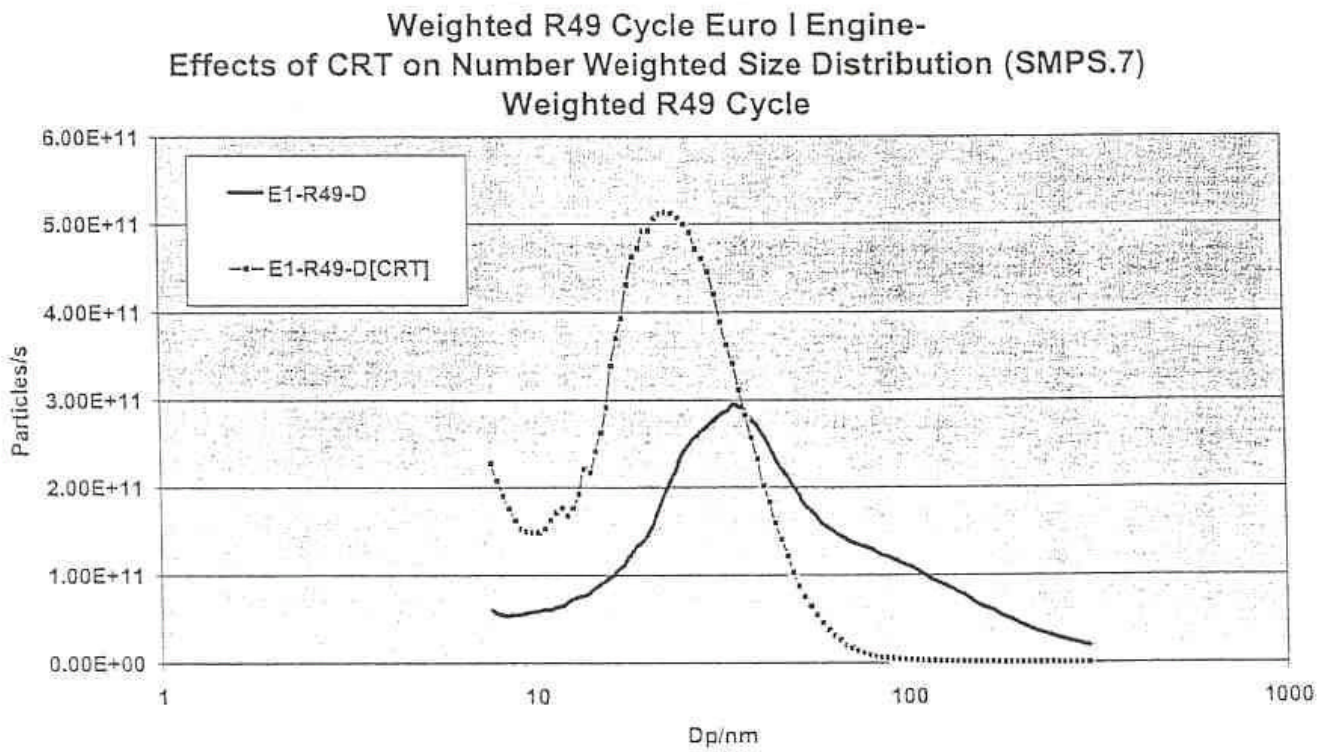
U of MN SAE 2001-01-0201



Aerosol nanoparticles drop as dilution temperature increases and for ULSD fuel

CORNING

Under some conditions, nanoparticles out of filters may increase



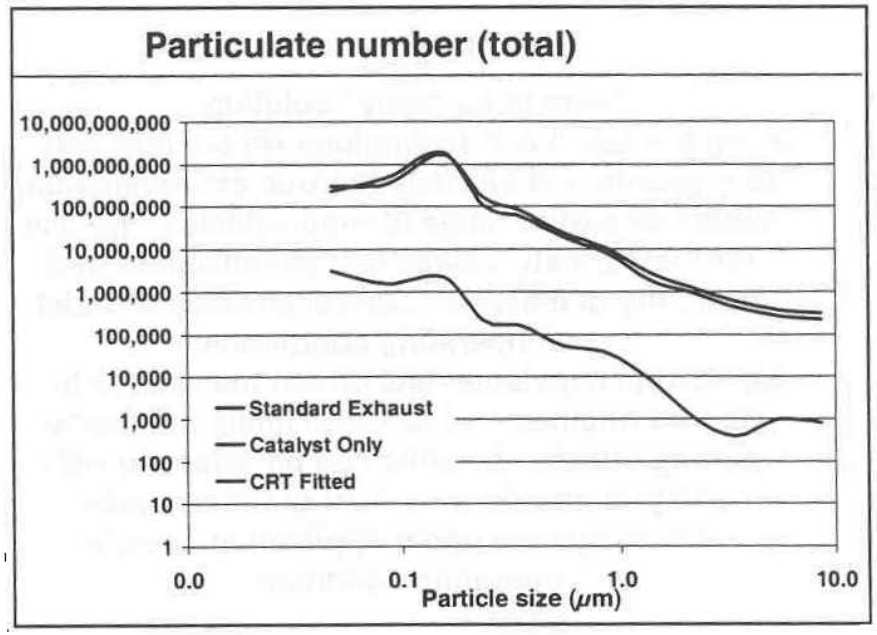
Using UK ULSD, nanoparticles increased with filter. Euro 1 engine. 50 ppm sulfur

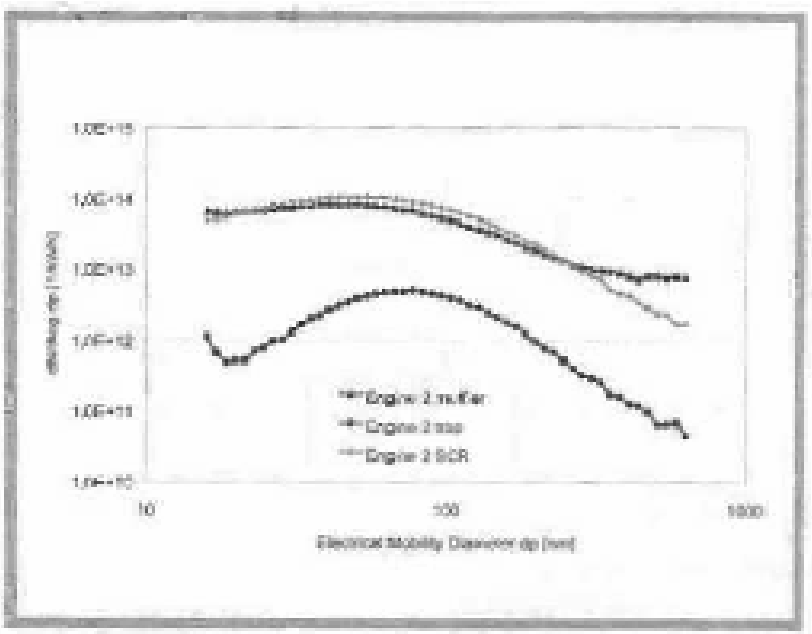
Ricardo (2) ImechE 12/01

<u>Hypotheses</u>: 1) Without soot present, aerosols nucleate and grow on their own, creating nanoparticles; but unfiltered exhaust plumes (high soot levels) show high nanoparticle concentrations 2) HT operation and catalysts generate sulfates - growing body of evidence on certain high-load modes and engines

CORNING

Catalysts and SCR drop PM by mass but leave PM numbers the same; Filters are effective





Filters drop nanoparticles by 2.5 orders of magnitude; DOCs have no effect

Millbrook Proving Grounds SAE TopTec 9/00

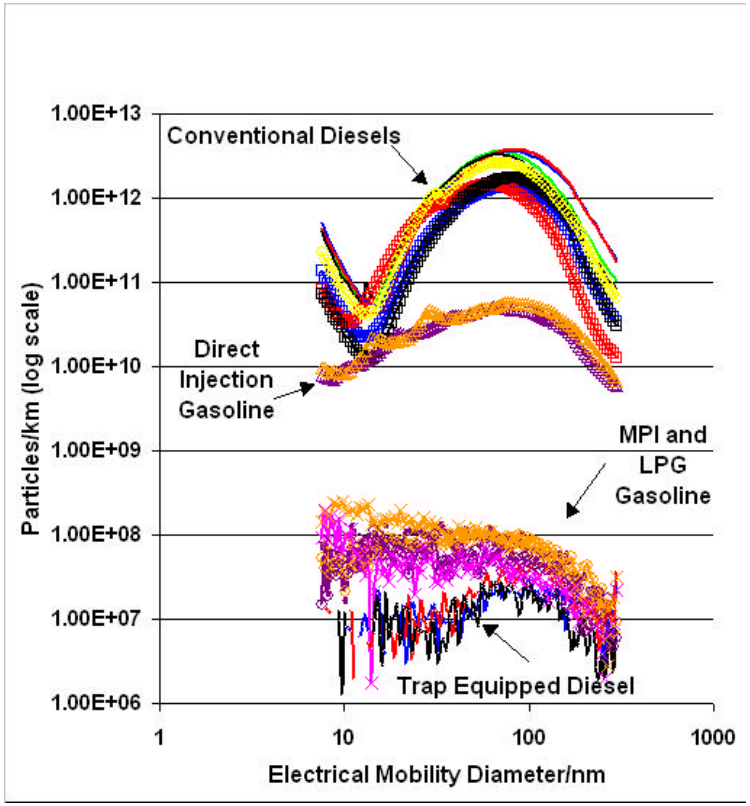
Filters drop nanoparticles by 1.5 orders of magnitude; SCR has no effect

Daimler Chrysler VDA 2000

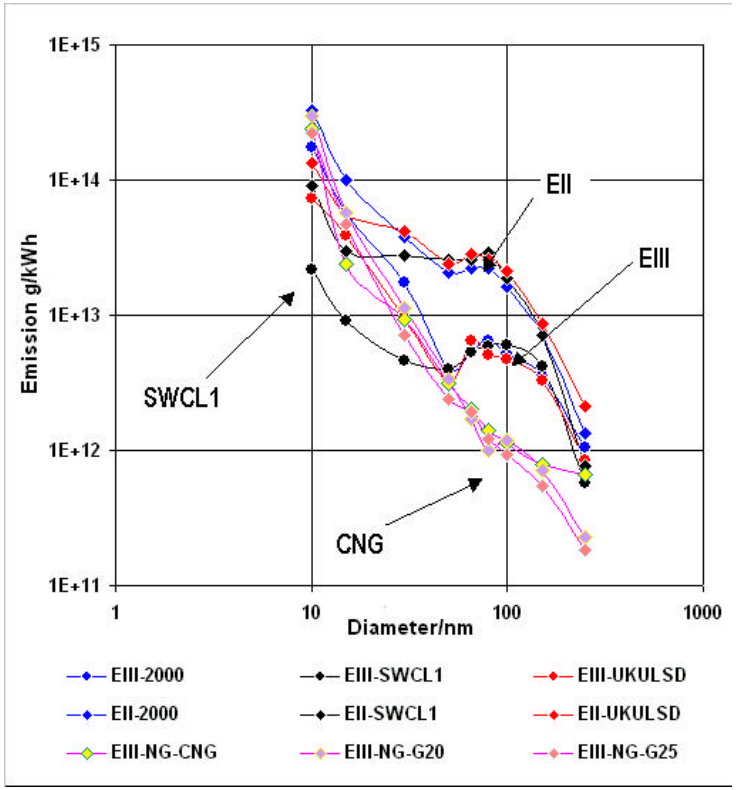
CORNING

Particle size distributions are compare for various technologies

Light Duty, 50 kph, NEDC



Heavy Duty, urban part of ETC



Study: Filters are effective in dropping carbon and aerosol nanoparticles, but HT modes can show little PM reduction

CONCAWE study, 1/01

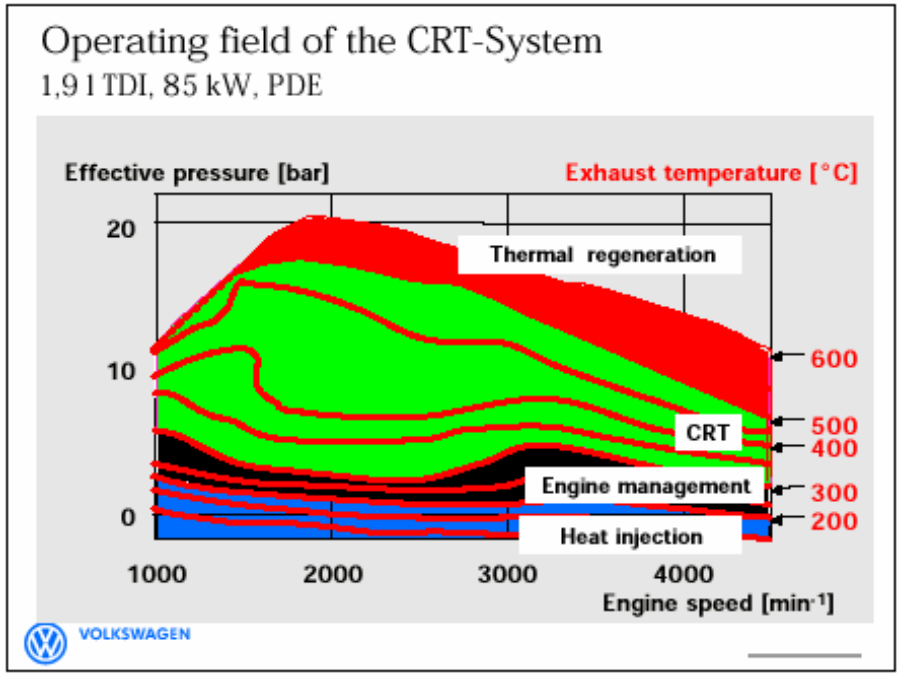
CORNING

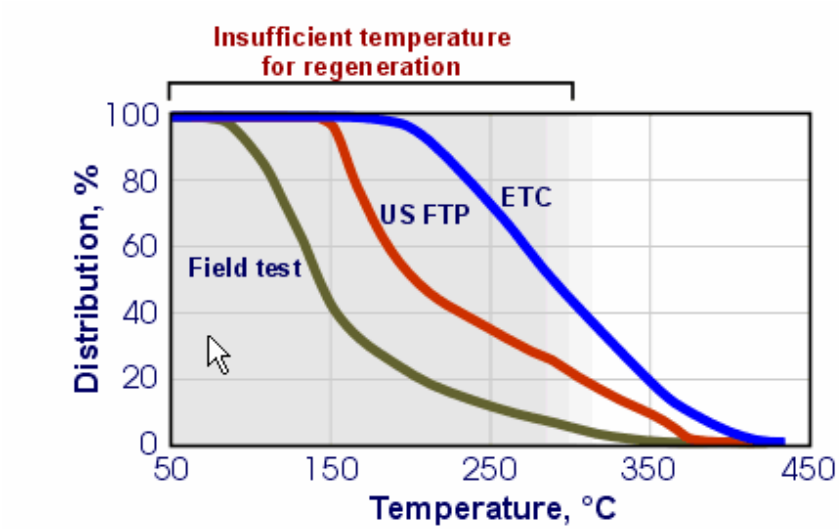
Diesel Particulate Filters

- Filter materials and configuration are improving
- Regeneration systems are being optimized
- Lube ash is emerging as next issue to address

CORNING
Discovering Beyond Imagination

Active filter regeneration systems will be needed for both light and heavy duty vehicles





HDV Temperature Distribution

Source: AVL 2001, SAE & Vienna

Peugeot described their post injection/DOC filter regeneration strategy.

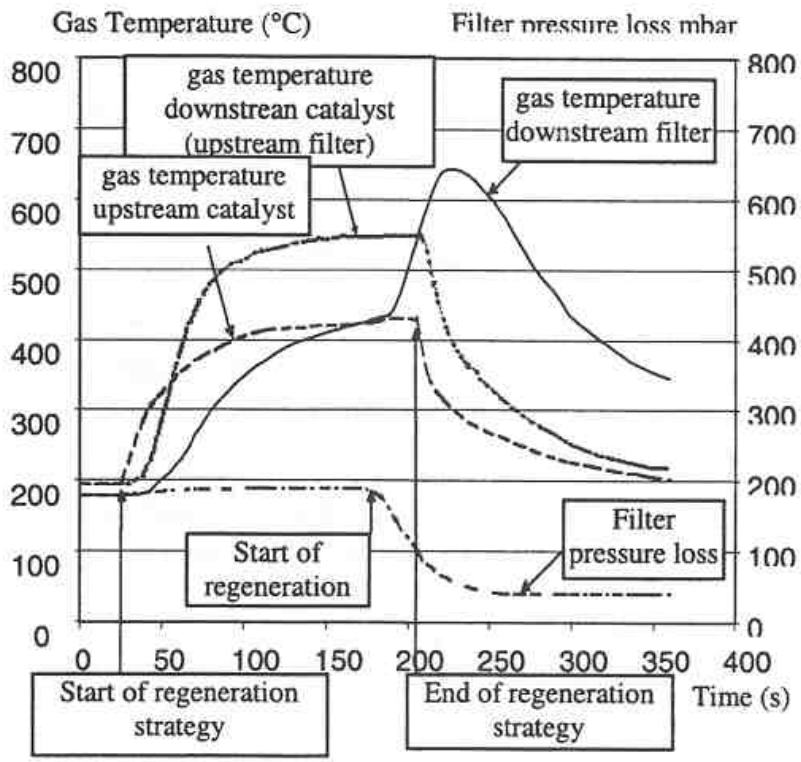


Figure 8. Example of exhaust gas temperature increase and particulate filter regeneration under steady state conditions

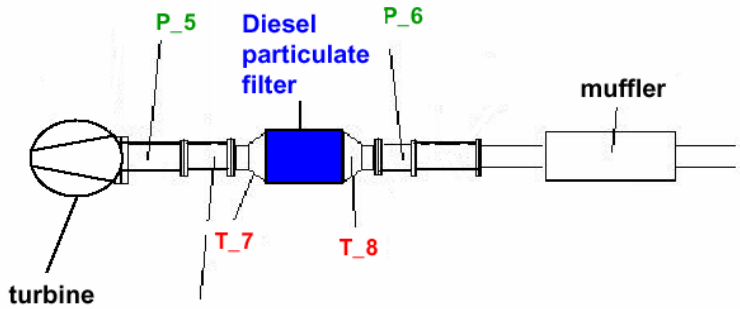
Late injection increases exhaust temperature, lighting off catalyst. Soot burns, and back pressure drops. Ce fuel catalyst used drop regeneration temperature

System comprises cerium FBC, post injection of fuel that is burned in a DOC, and SiC filters with pressure sensors.

- **State of DOC is important**
- **Torque is affected, but compensated for using injection strategy and turbocharging**
- **OBD on filter**
- **Minimized fuel penalty**
- **Fuel effects**

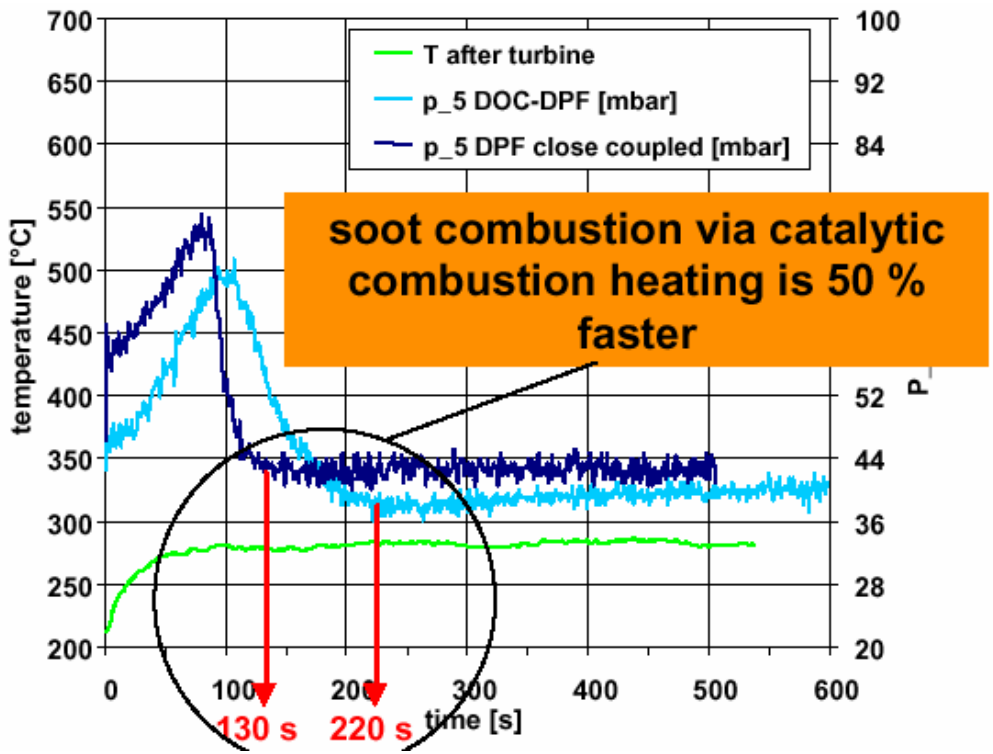
Peugeot SAE 2000-01-0473

Replacing the DOC and FBC with catalyst on the filter saves regeneration time and fuel



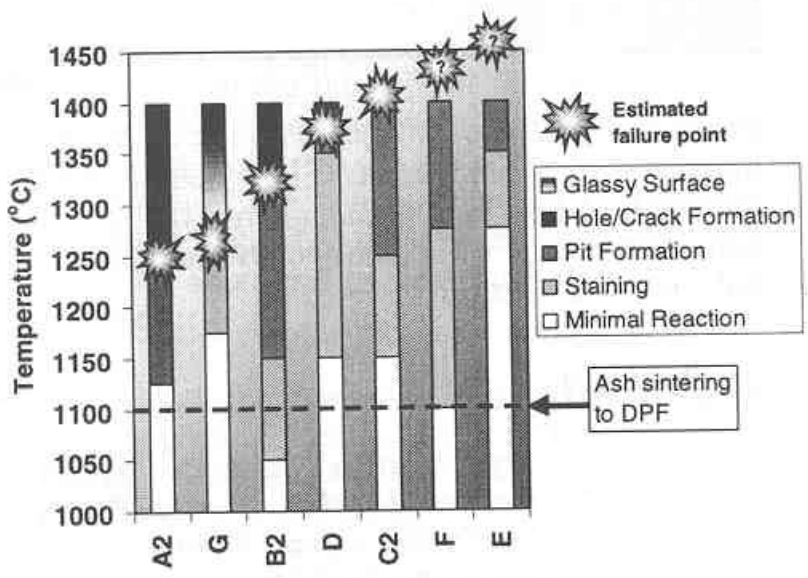
dmc2 SAE 2001-01-0907

- 2 liter common rail PSA engine
- SiC filter
- regeneration temperatures are the same

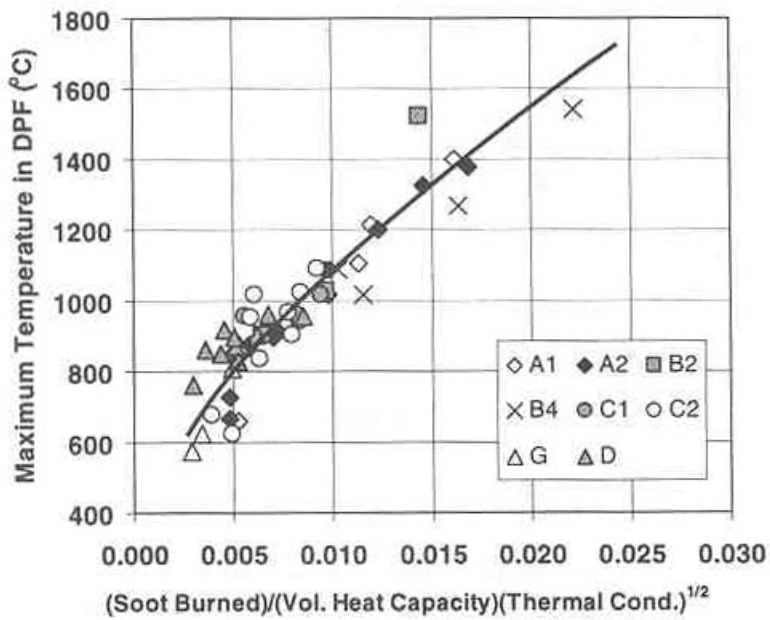


CORNING

“Durability” of DPF may be more dependent on ash than on filter material; 1100°C max T recommended



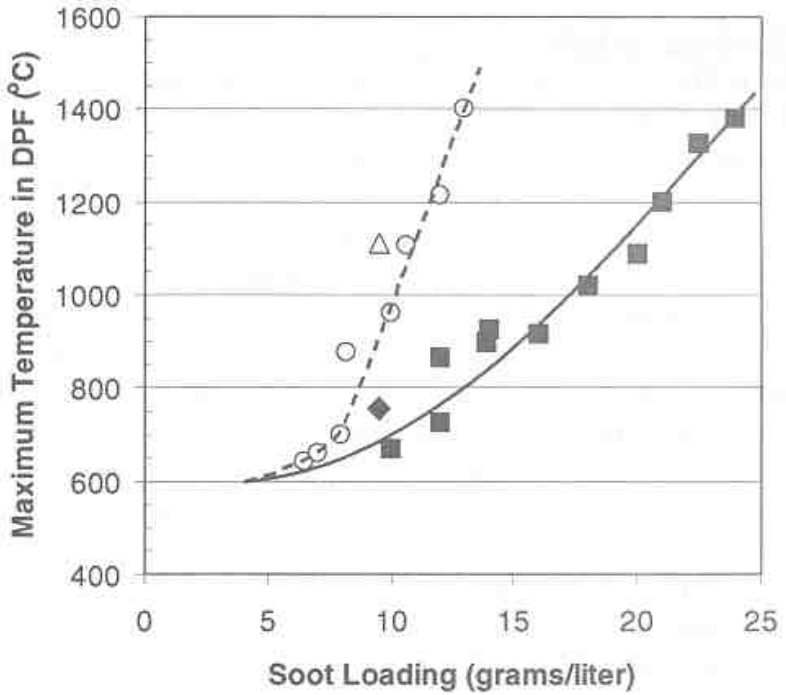
Ash sintering begins at 1100°C for all filter compositions. High-Fe ash; A2: cordierite; G: SiC, B&C: Zr phosphates, D to F: alumino silicates.



Maximum peak temperature of the filter is related to soot loading and thermal properties of the filter.

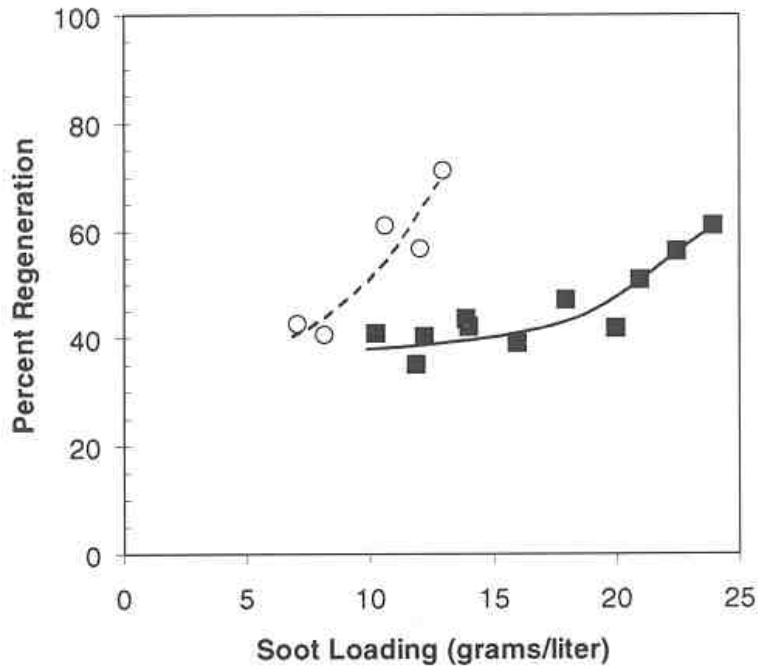
An improved cordierite filter has better durability

New cordierite material significantly drops peak temperature.



Maximum temperature during uncontrolled regeneration for RC 200/19 (solid squares) and EX-80 100/17 (open circles). 5 cm x 15 cm filters

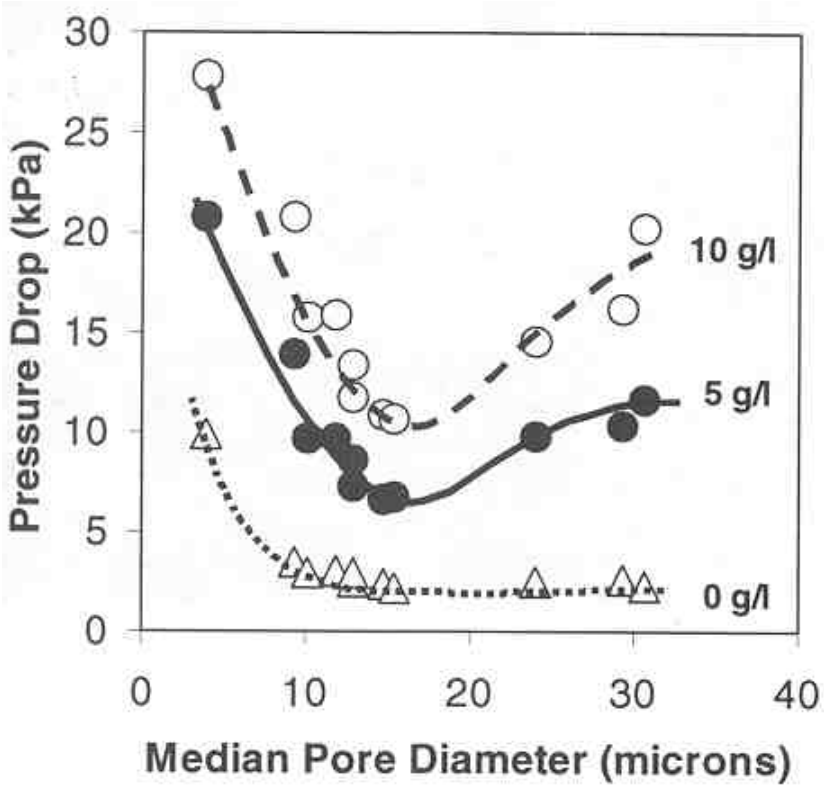
Increased thermal mass decreases the percentage of soot that is burned.



Percent regeneration versus soot loading for EX-80 100/17 (open circles) and RC 200/19 (filled squares). 5 cm diam X 15 cm long

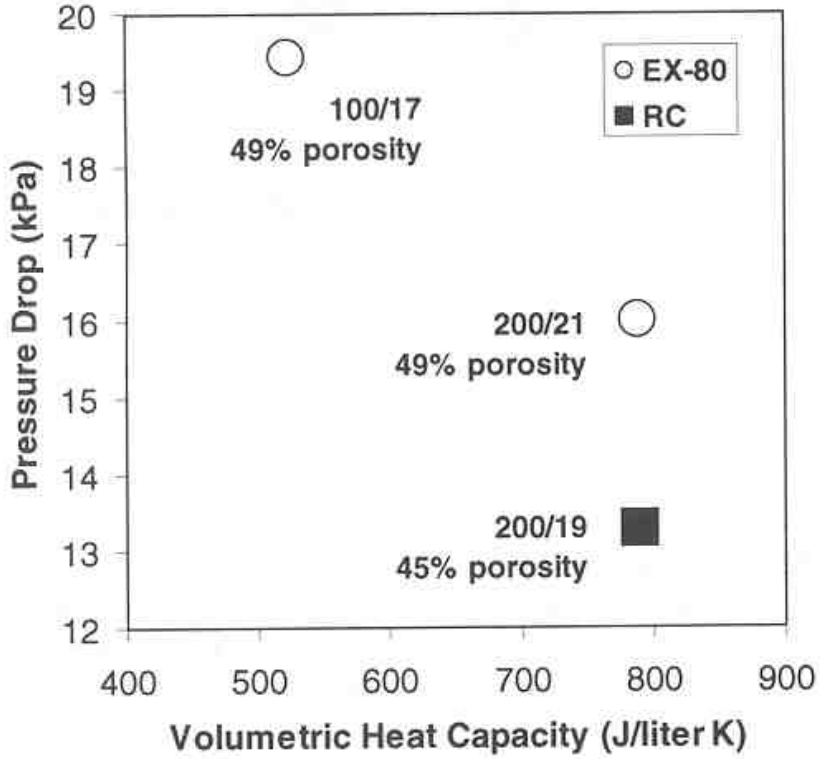
Porosity is designed to minimize back pressure for high thermal mass cordierite filters

Pressure drop of loaded filters is minimized at a pore size of about 12 um.



Pressure drop (26.25 scfm flow rate) at 0, 5, and 10 grams/liter soot loading versus median pore diameter (d_{50}) in micrometers

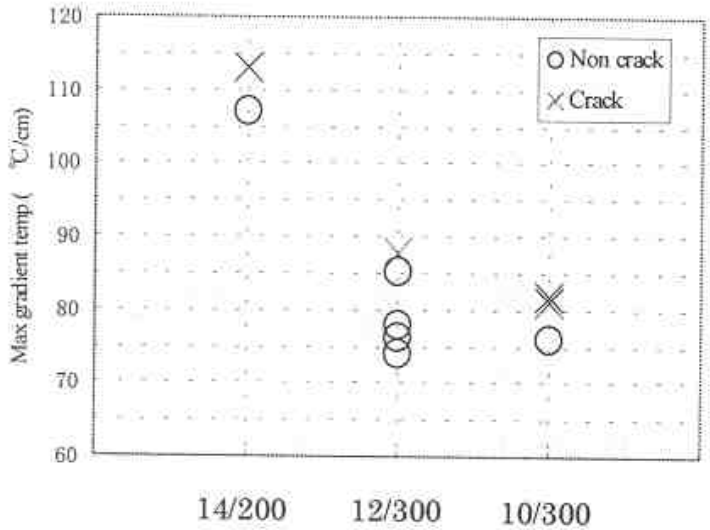
Durable filter materials need to balance pressure drop and thermal mass.



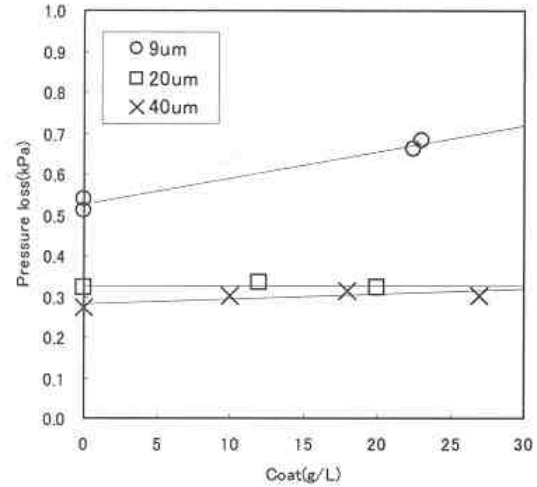
Pressure drop (10 g/l artificial soot loading, 26.25 scfm air flow) versus bulk filter volumetric heat capacity at 500°C for the RC 200/19 filter (solid square) compared to the EX-80 material in 100/17 and 200/21 filter geometries (open circles).

CORNING

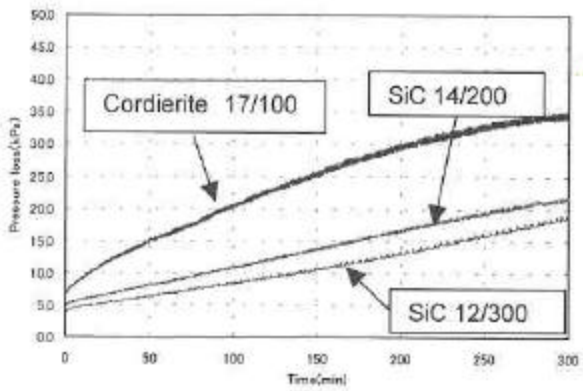
Pore structure and cell geometry affect filter durability and back pressure



Filter failure largely dependents on thermal gradients, which depend on cell geometry. SiC.



Pressure drop for catalyzed filters is affected by pore size. 47% porosity, alumina wash coating, 2 m/sec flow.

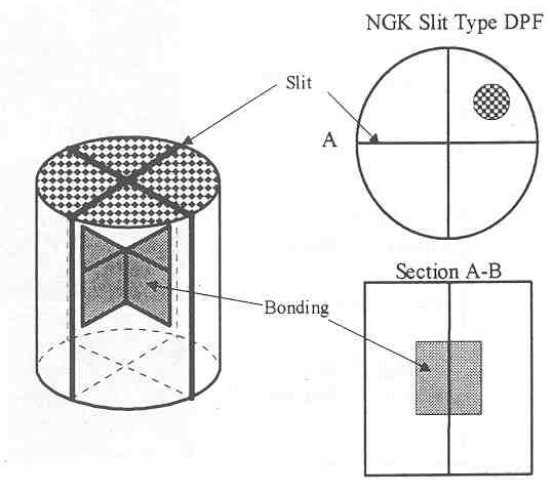


2 liter DI engine run at 3000 rpm and 60 Nm load using 350 ppm sulfur fuel with 25 ppm cerium fuel-borne catalyst

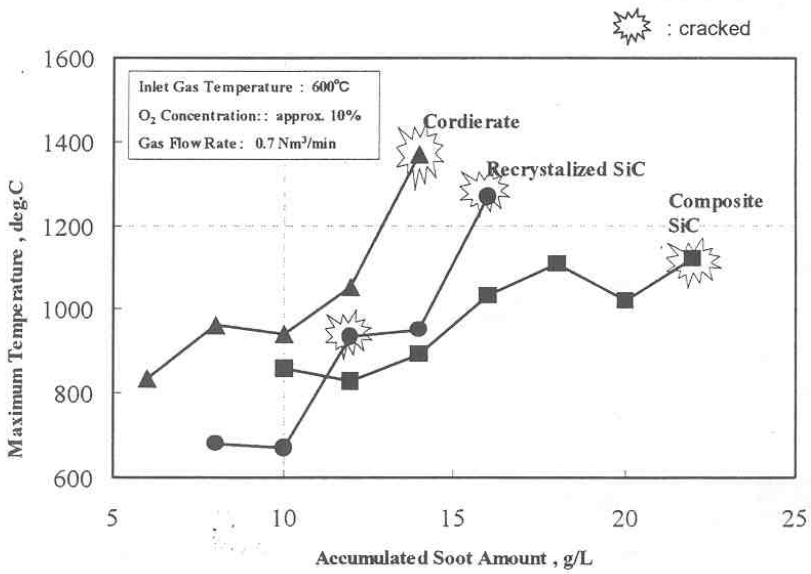
Ibiden SAE 2001-01-0191

CORNING

New SiC design and materials show enhanced filter durability

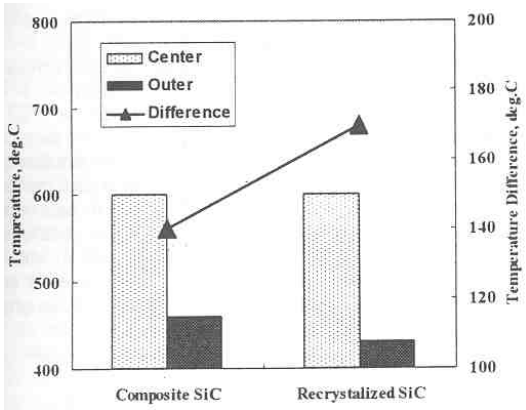


Four quadrants are cemented together only in the central region. The quadrants thus relieve thermal stress much more efficiently.



New composite SiC has more capacity for soot. Composite is SiC bonded by Si metal.

Because of high thermal expansion, SiC needs to be segmented with flexible joints to survive

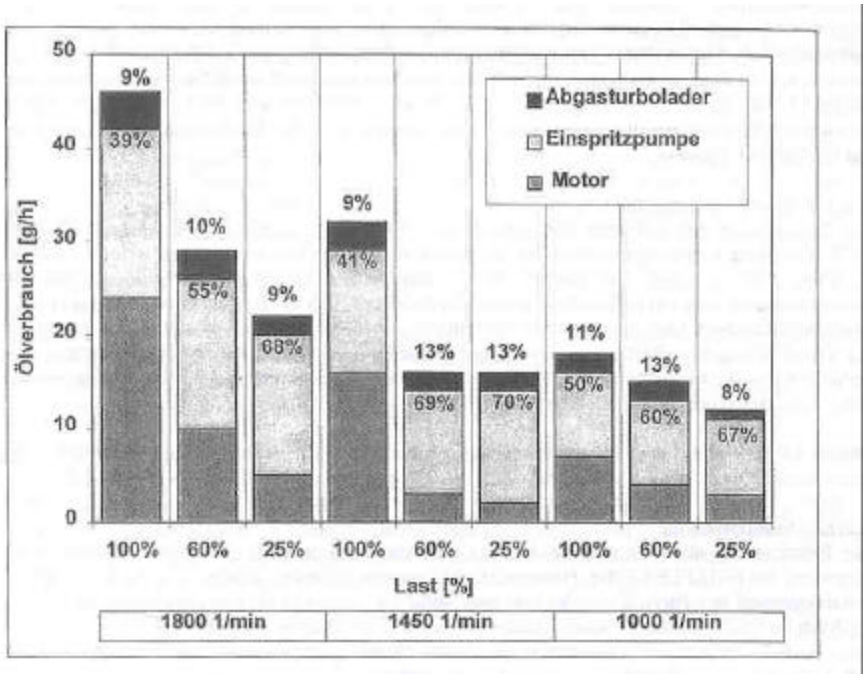


Thermal gradients are reduced with newly bonded material.

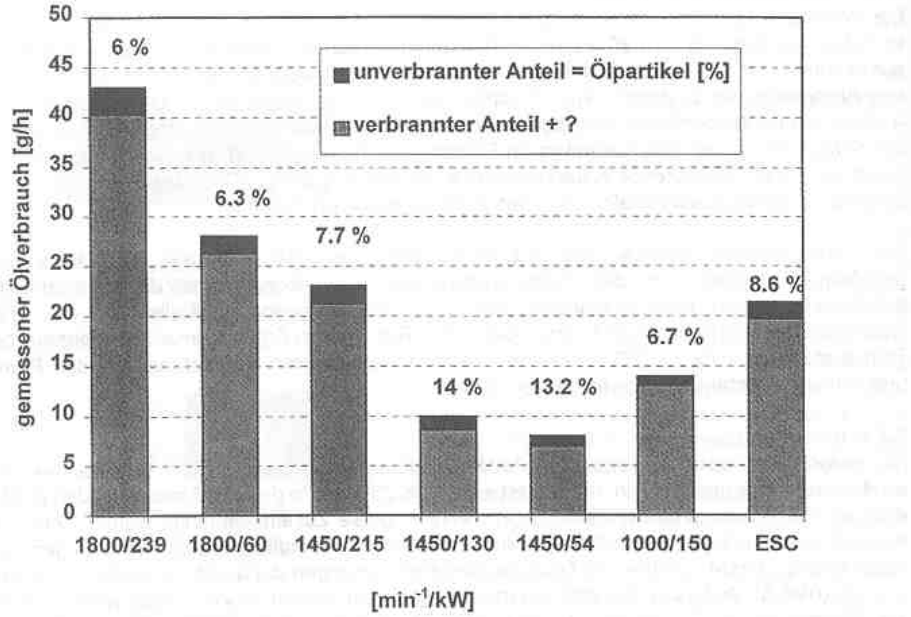
NGK SAE 2001-01-0192

CORNING

The sources and effects of lube oil ash on HDD are characterized



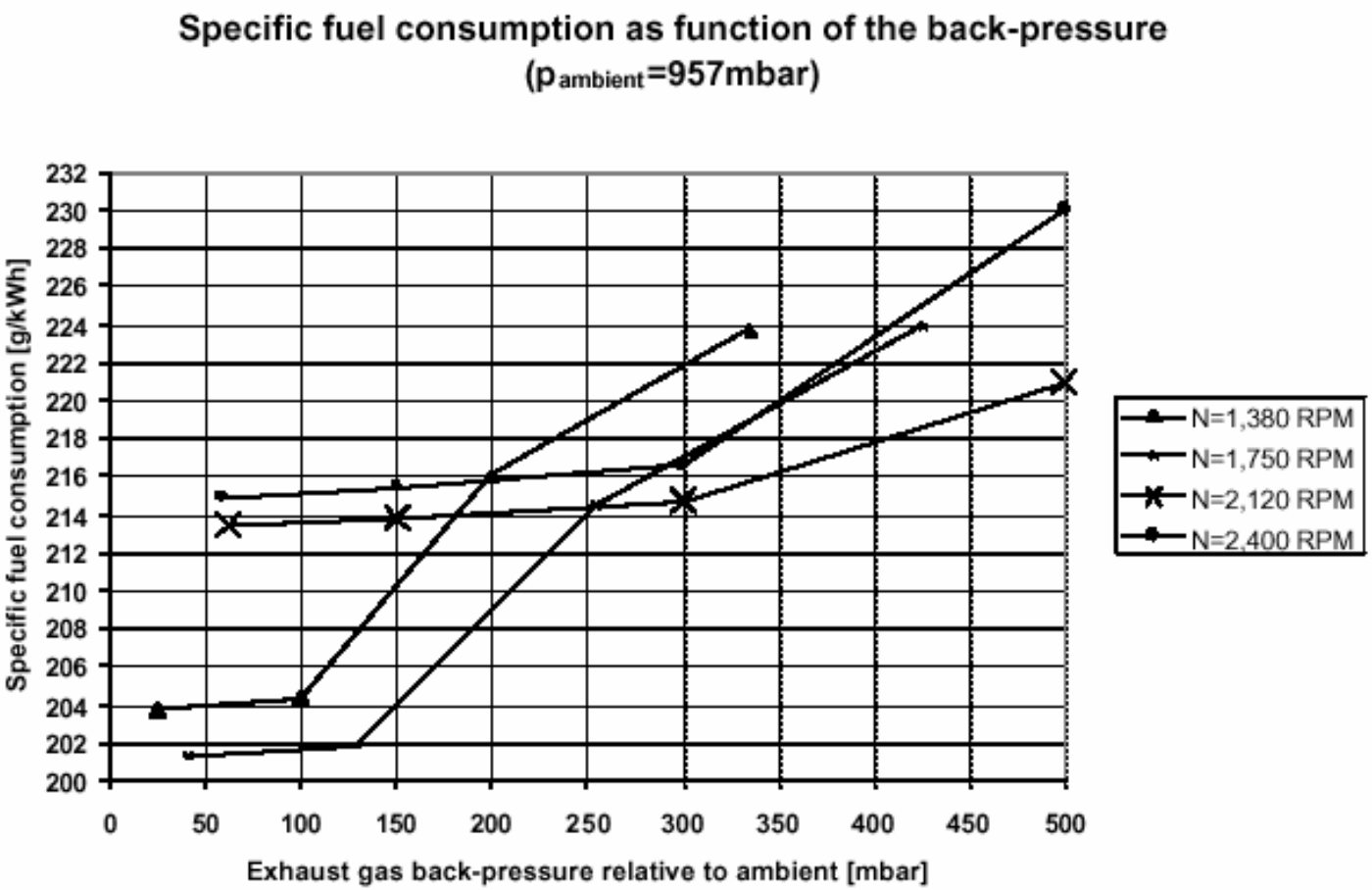
Depending on engine speed and load ("Last"), 39 - 70% of the lube oil ash (Ölvesbrauch) comes from the fuel injector pump (Einspritzpumpe).



The composition of the oil ash (genuessener Ölvesbrauch) varies minimally as a function of conditions. Unburned oil is 6 to 13%.

To hit Eurpean regulations, need to drop ash rate from 3.7 to 0.5 mg/kWhr
Need P <0.002%, S<0.25%
Converting lube oil lubricated pump to fuel - lubricated pumps

At full load and rated RPM, simulations show that 200 mbar back pressure can be tolerated with little fuel penalty; slightly higher back pressure: huge impact



Iveco Cursor 8

7.8 liter

pump nozzle

VGT-turbo

Might explain why some applications see high fuel penalties, and others see none.

Swiss EPA Environmental Document 130

Simulated results (G-T Power from Gamma Technologies). Full load fuel consumption increases if a threshold filter back pressure is exceeded

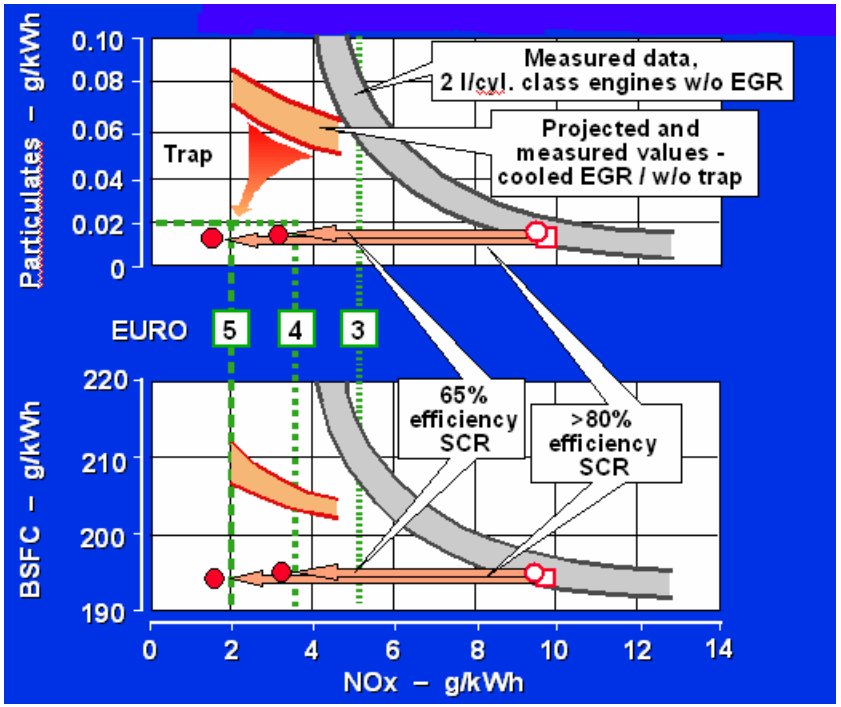
CORNING

NOx Solutions

- Technology is focused on HDD (regulations)
- Europe is moving towards SCR
  - SCR for long haul, beginning in 2005
  - Filters and EGR for urban
- NOx traps are developing rapidly

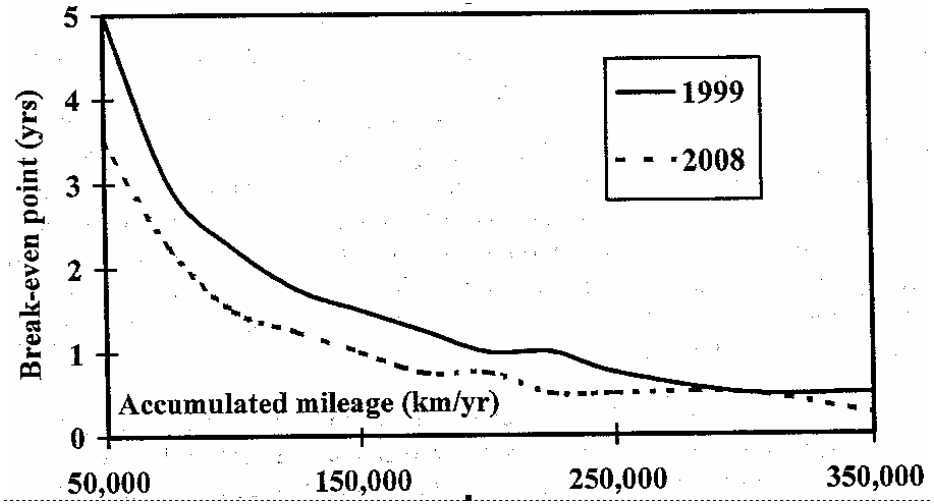
CORNING
Discovering Beyond Imagination

Due to high fuel prices and fuel savings from operating down the NOx/PM tradeoff curve, Europe is adapting SCR



65% efficient SCR enables operation at high NOx and low fuel consumption. AVL SAE TopTec 9/00

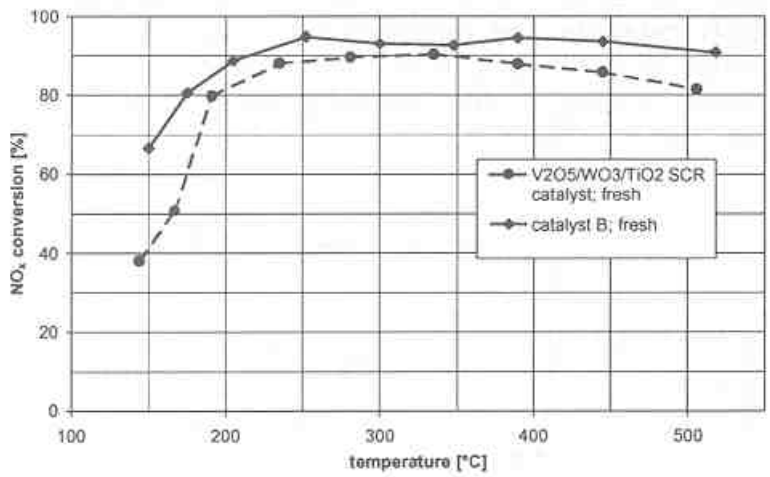
Item or Variable:	Estimated item cost (€):
SCR system	3100
EGR plus trap system	2500
High grade urea	0.22 per litre
Diesel fuel	0.68 per litre
Fuel consumption	34 litres/100 km
Urea consumption	3% of fuel consumption
Annual mileage	50,000-300,000 km/yr



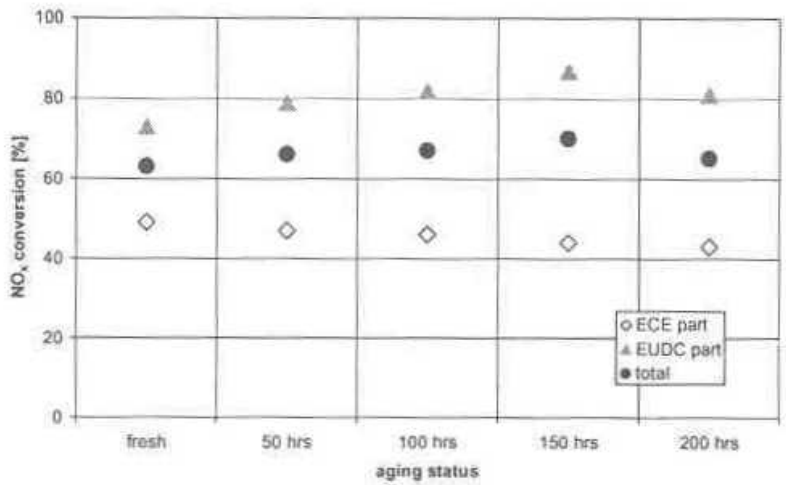
The SCR payback period in Europe is less than a year in 2008, but more than 3 years in the US; Open University - ImechE 12/01

CORNING

Zeolite SCR catalysts are being developed and being evaluated for LDD.



Ion-exchanged zeolite (B) has similar NOx performance as standard SCR catalyst.



Zeolite catalyst shows no deterioration with aging to 200 hours. LDD.

- 4 l TDI
- <50 ppm S
- 8.6 l catalyst on 400 csi metal

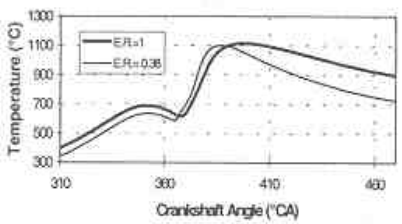
dmc^2 SAE 2001-01-0514

CORNING

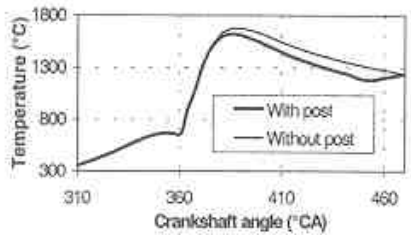
Using NOx traps to hit Euro 5 certification level, 3.8% fuel penalty is measured; 2.6% to hit Euro 4;

1.6 l single cylinder test engine

EGR effect

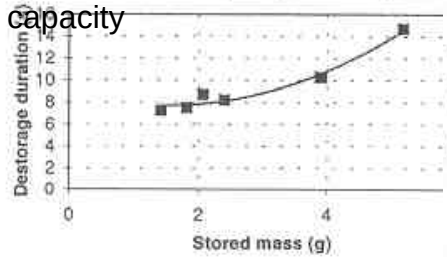


Post-injection effect

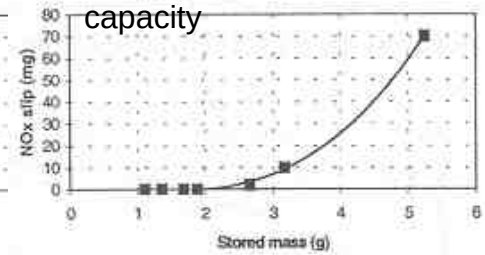


With EGR, rich post injection has minimal effects on peak cylinder temperatures. Engine durability expected to be uneffected.

Regen time vs. NOx capacity

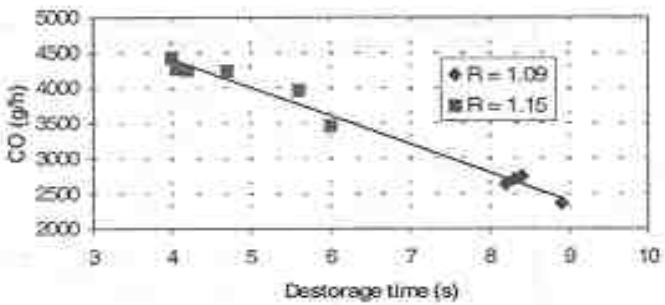


NOx emission vs. NOx capacity

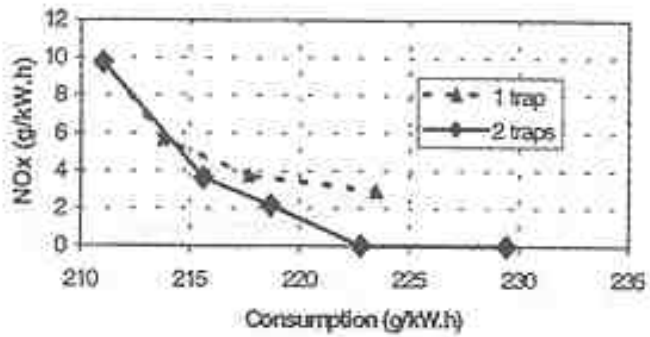


Because regeneration time and regeneration NOx emissions increase disproportionate to stored NOx , maximum of 3 g of NOx capacity was chosen. Equiv Ratio = 1.09

Influence of CO on regeneration



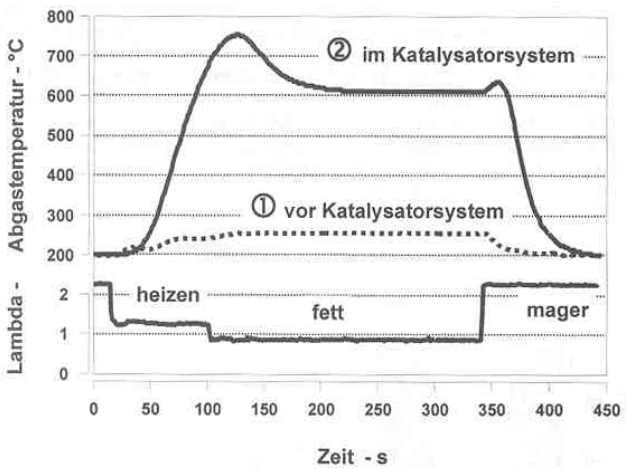
Regeneration time is most dependent on CO content. Derived under a variety of fuel injection timings and quantity.



Two parallel traps (SVR = 3.1) results in lower fuel consumption. Increased regeneration time is offset by higher NOx efficiency.

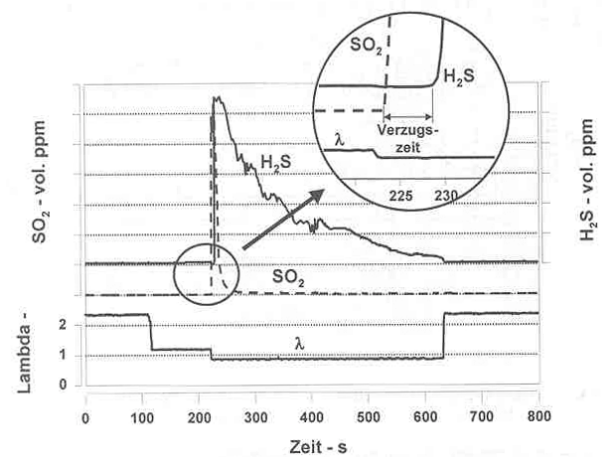
CORNING

A cycled NOx trap desulfation strategy prevents H_2S formation

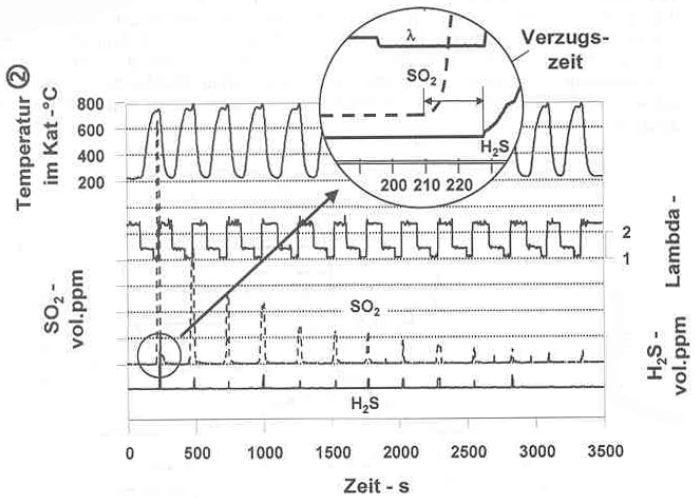


Stepped lean and rich modes are used to generate rich HT modes for NOx trap desulf. 50 km/hr.

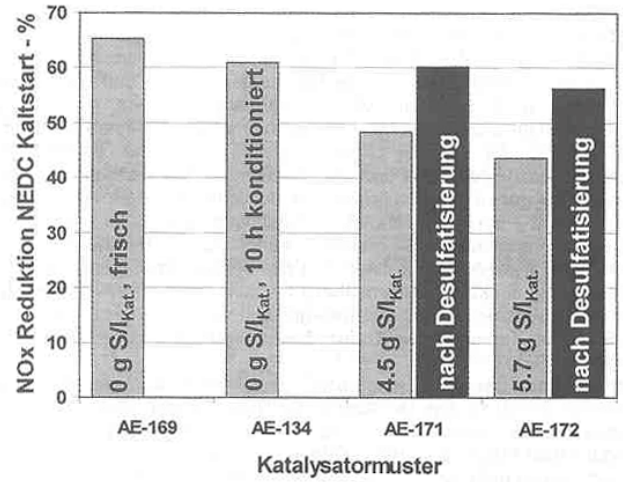
H_2S generation is a problem in rich conditions, but lags SO_2 formation by 8 sec.



2 l HSDI Peugeot
400 csi NOx trap and DOC
2.5 l each 3.2 g/l Pt

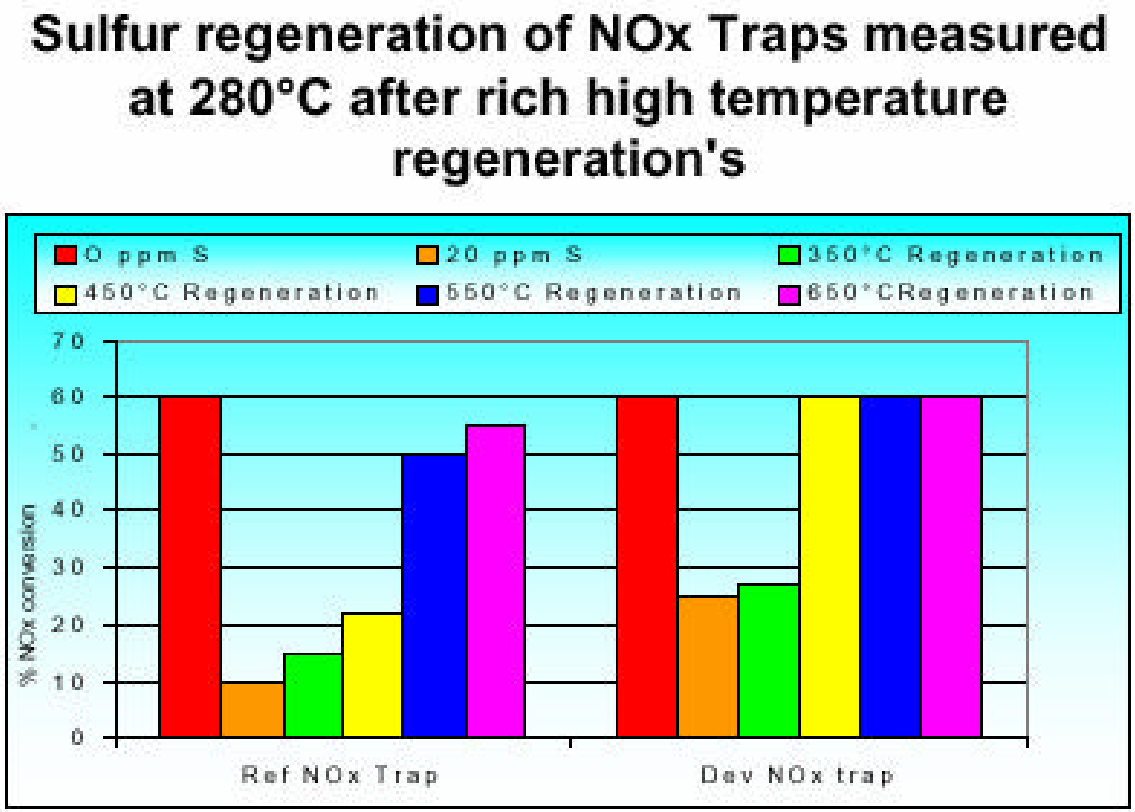


One long desulfation mode compared to cycling at 2 different sulfur loads. With cycled desulfation, NOx performance is brought to original sulfur-free performance.



Cycled rich-lean modes prevents H_2S generation

NOx traps are in development that will desulfate at as low as 450C



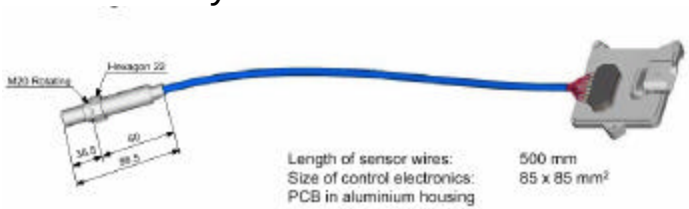
The development NOx trap returns to original performance after desulfating at 450C

JMI AVECC conf. MECA.org

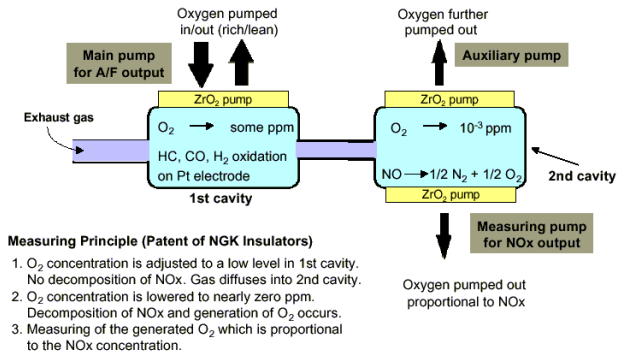
CORNING

A NOx sensor with ± 5% reproducibility and excellent transient response is being developed for introduction in diesel applications in 2003

Layout of the sensor



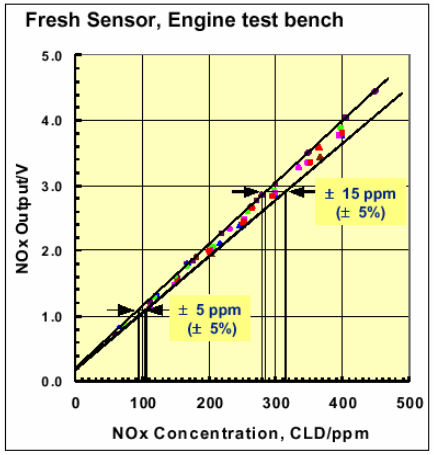
Principle of operation



Measuring Principle (Patent of NGK Insulators)

1. O_2 concentration is adjusted to a low level in 1st cavity. No decomposition of NOx. Gas diffuses into 2nd cavity.
2. O_2 concentration is lowered to nearly zero ppm. Decomposition of NOx and generation of O_2 occurs.
3. Measuring of the generated O_2 which is proportional to the NOx concentration.

Accuracy



- 1000rpm/5kgm
- 1000rpm/15kgm
- 1500rpm/5kgm
- 1500rpm/10kgm
- 1500rpm/15kgm
- 1500rpm/20kgm
- 2000rpm/5kgm
- 2000rpm/20kgm
- 2500rpm/5kgm
- 2500rpm/10kgm
- 2500rpm/20kgm
- 3500rpm/5kgm
- 3500rpm/10kgm
- 3500rpm/20kgm
- 4000rpm/5kgm
- 4000rpm/10kgm
- 4000rpm/15kgm

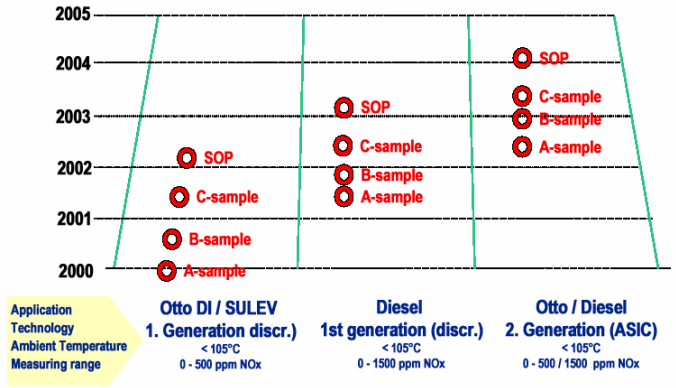
Diesel Engine:
2.5L Turbo-charged

Sensor position:
0.8m downstream of turbo

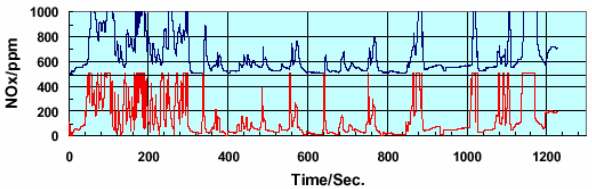
Gas temperature: 190 ~ 760 °C
O_2 concentration: 1.1 ~ 14.7%
NOx concentration: 50 ~ 450ppm

5th generation
NGK electronics

Commercial introduction timeline



Transient Response



CLD gas analyzer
(500ppm offset for clarity)

NGK NOx sensor

NGK and Siemens literature

CORNING

NOx Notable Mention

- High (+80%) efficiency SCR system had +40% PM with 50 ppm sulfur fuel, due to sulfate formation. At 15 ppm sulfur, there was a 40% reduction in PM. dmc^2. (VDA 2000)

- NOx trap desulfurization is best done in stages: hotter at first, followed by richer later on. (Renault SAE 2000-01-1874)

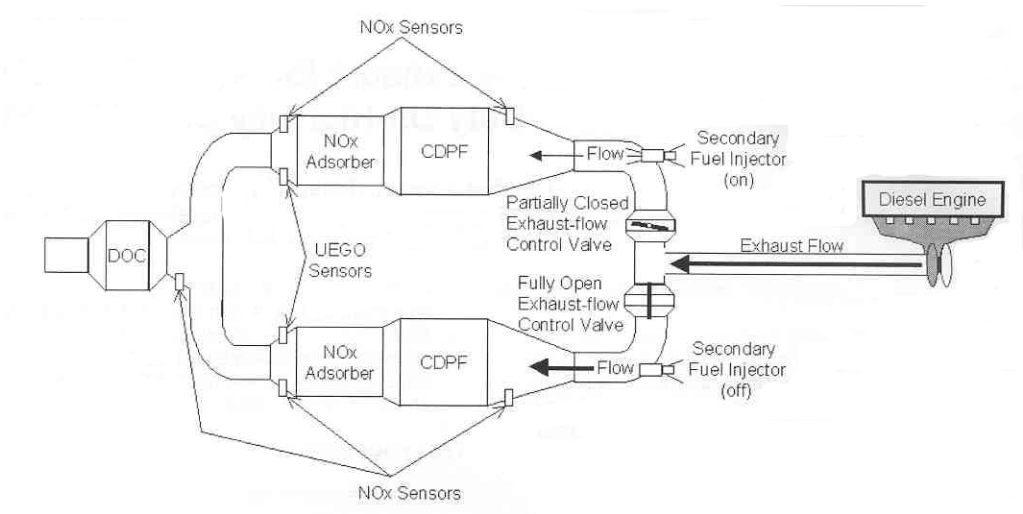
Integrated NOx/PM Solutions

“Package deals” are hitting US2007 regulations

Synergies between NOx and PM remediation could make combo systems more attractive than filters alone (Toyota DPNR)

CORNING
Discovering Beyond Imagination

A 5.9 liter 1999 engine achieved 93% reductions in NOx and PM in transient testing



One leg is in restricted flow regeneration while other leg is adsorbing.

1999 5.9 l Cummins ISB
19 l of DPF and 7l of NOx adsorber on each leg
NOx adsorber aged 10 hrs
3 ppm sulfur

Next Steps:

Reduce system to one leg
Test and implement desulfation cycle

(US EPA SAE 2001-01-1351)

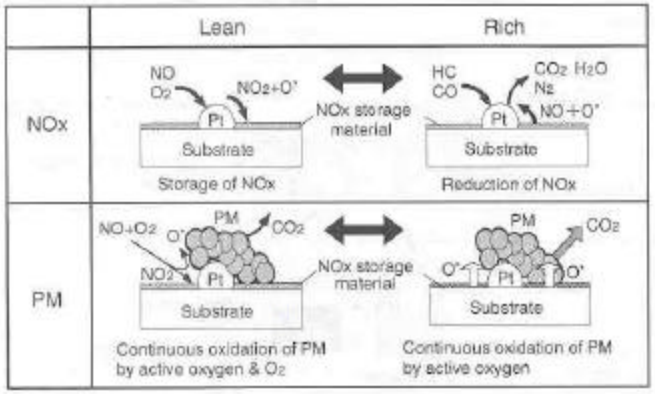
HDDE Hot Start Transient

	baseline g/bhp-hr	test g/bhp-hr	Change %
NOx	3.66	0.25	-93%
HC	0.29	0.28	-3.5%
PM	0.089	0.002	-92%
FC	--	--	+2.3%

0.15 g/bhp-hr NOx achieved with cooled EGR

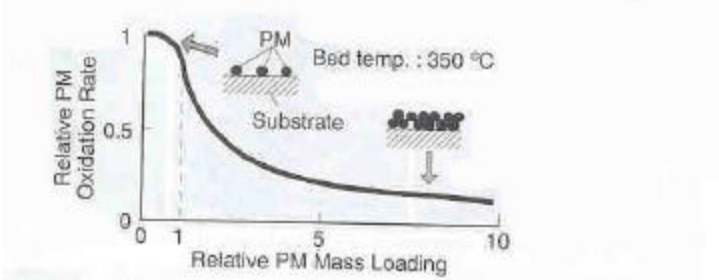
CORNING

New integrated DPF / NOx trap is described; gets 90% reductions in PM and NOx



The principle of combination diesel particulate/NOx reduction system. PM is oxidized in both lean and rich conditions.

At a bed temperature of 350ºC, a maximum PM load rate of 3 g/l is tolerable before the catalyst blocks. Typical balance point temperature = 250ºC

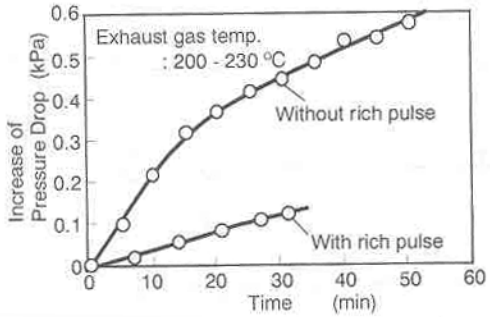


Relationship between the PM mass loading and the PM oxidation rate

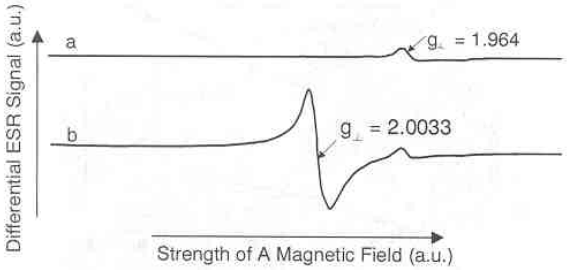
$NO + 1/2\ O_2 = NO_2$

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

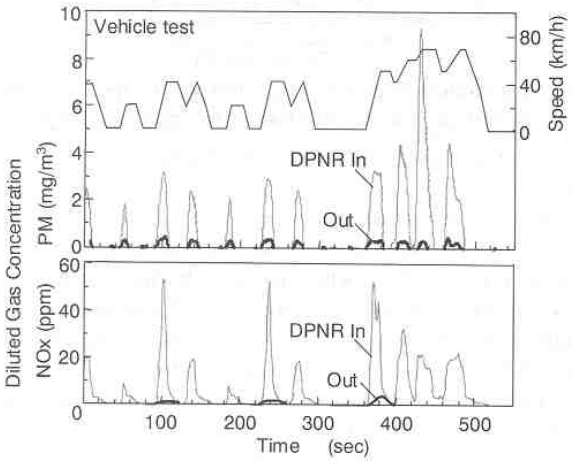
"$1/2O_2$" is the "free oxygen", and is generated on the forward and reverse reactions



Periodic rich pulse causes PM to oxidize



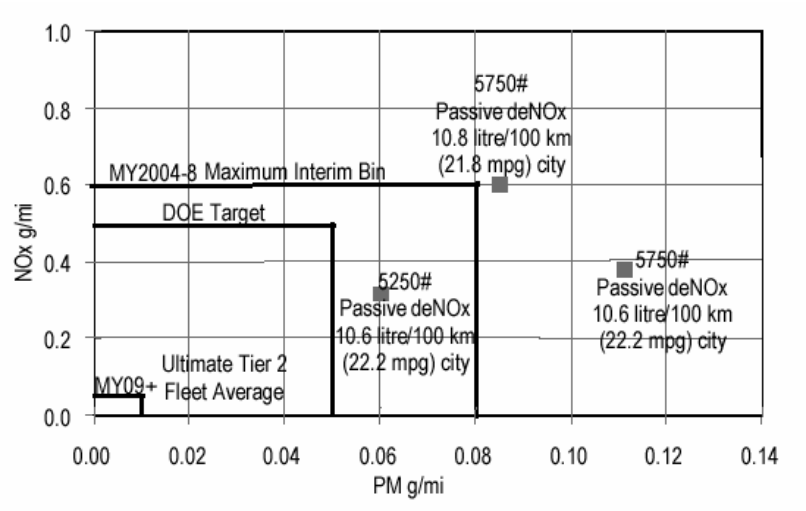
Influence of air-fuel ratio modulation on ESR spectra in the DPNR catalyst : (a) under lean air-fuel ratio of steady state at 300 °C and (b) under lean air-fuel ratio of 5 sec after rich air-fuel ratio at 300 °C.



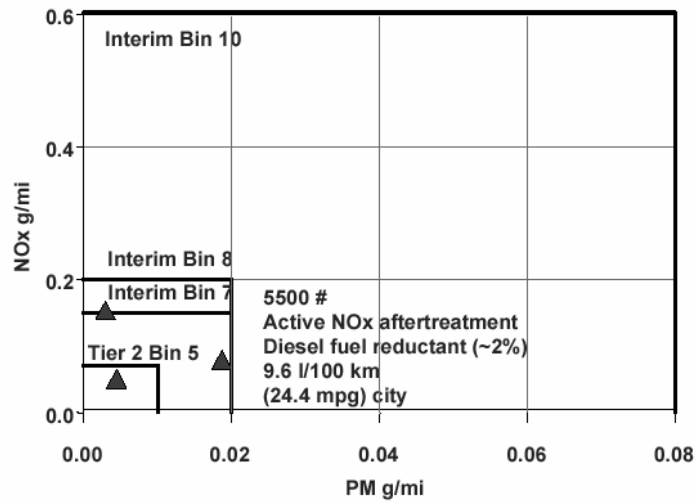
DPNR system drops NOx and PM by 90%

CORNING

A 1997 4.2 liter SUV engine achieved Bin 5-7 emissions levels with retrofit emission control

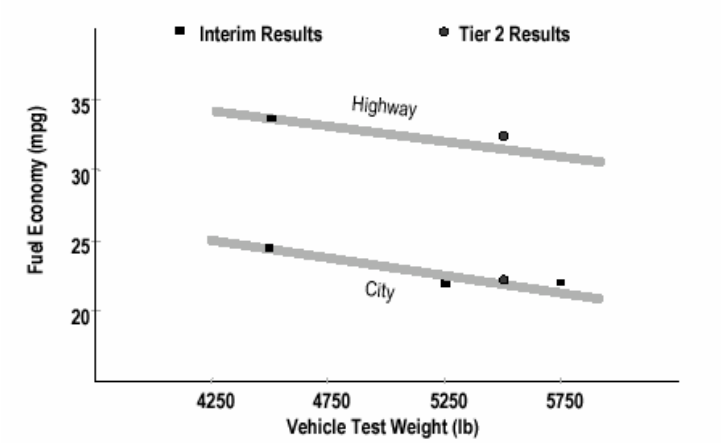


Stock 1997 Euro 4.2 liter engine was dropped from 1.8 gpm NOx and 0.3 gpm PM to hit Bin 10 by adding cooled EGR, VGT, advanced fuel system, and 10% deNOx cat.



Bin 5 was hit (once out of three) by adding a DPF and NOx trap. Diesel fuel reductant. No FTP cold start. Engine dyno simulation using ULSD fuel. System size not disclosed.

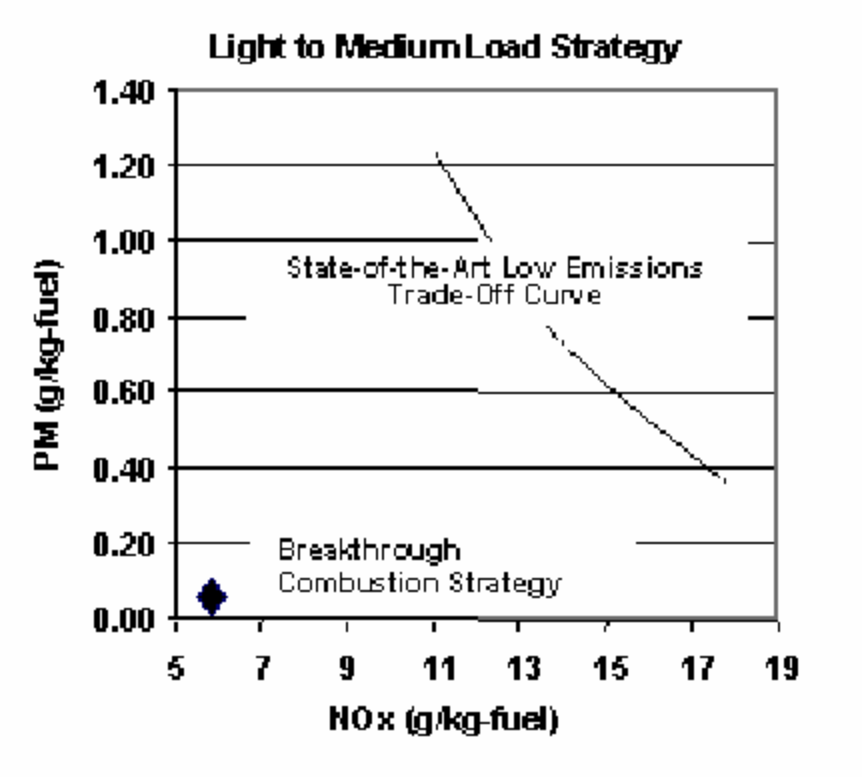
Cummins SAE 2001-01-2065



59% better fuel economy observed vs. similar gasoline engine on SUV (within 2%). Bin 10 and Bin 5 configurations had similar results.

CORNING

One engine company is confident they can hit Tier 2 Bin 5 with a LDT in 2007



New combustion control technology significantly drops engine out NOx and PM.

Authors have a great deal of confidence that Bin 5 can be hit in 2007 with a LDT if the ULSD fuel is available.

DDC SAE 2001-01-2062

Summary and outlook

- The nature of nanoparticles is becoming understood. Exhaust plume analyses are the key.
  - Europe is considering regulating soot particle numbers
- Filter regeneration strategies are evolving.
  - LDD and OEM HDD will have similar needs in the future. Retrofit will need active systems and durable filters.
- NOx solutions are available to achieve 70%+ efficiency; some NOx traps are getting 90%+
  - Europe is heading toward SCR for long haul, and filters and EGR for urban in 2005
  - NOx adsorbers are advancing through engineering stage
- Integrated PM/NOx systems are being developed
  - “DPNR-type” systems are showing NOx/PM synergies
- Solutions are making diesel as clean in all respects to natural gas and gasoline