Recent Developments in Integrated Diesel Exhaust Emission Control Technologies

Mining Diesel Emissions Conference

November 3-4, 1999

Presentation Outline

- Introduction
- Targeted Emissions
- Control Technologies for PM and Toxic Emissions
- Control Technologies for NOx Emissions
- Control Systems
- Conclusions

Introduction

- Significant Progress Has Been Made in Reducing Emissions from Diesel Engines
- Diesel Powered Vehicles Remain a Significant Source of NOx, PM, and Toxic HC Emissions
- Emission Control Technologies Exist to Substantially Reduce Emissions from Diesel Engines
- Technologies Can Be Used in Combination to Substantially Reduce All Emissions

The Future Diesel Challenge

- Current Standards Focus on NMOG, NOx, PM, CO, and Formaldehyde Emissions in Terms of grams/bhp-hr or grams per mile
- California’s Toxic Air Contaminants and EPA’s Urban Air Toxics Initiatives
- Particle Number Issues
- Therefore, the Emission Challenge Will Be More Complex
    - >200 Species of HC
    - Three Major Species of NOx
    - PM (many species, size range <10 nm to >2 microns, number, liquid and gaseous HCs, solid carbon, carbon/organic combinations and sulfur oxides)

The Future Diesel Emission Challenge

- Can All Facets of the Diesel Emissions Issue Be Addressed?
  - * Are Control Technologies Available to Remove Both Diesel PM and the Other HC-Based Toxic Emissions?
  - * Are These Control Strategies Compatible with Further Reductions in NOx Emissions?
- Yes, If an Integrated Approach Is Used
  - * Advanced Engines, Integrated Emission Control Technologies, and Clean Fuels

Technological Solutions

- Existing Emission Controls Can Greatly Reduce Diesel Emissions
  - Oxidation Catalysts, Particulate Filters, Fuel-Borne Catalysts in Combination with Exhaust Controls, Coatings, Modified Engine Components
- Advanced Emission Control Technologies
  - NOx Catalysts, SCR, Plasma Technology, Combined Systems
- New Engine Technologies
  - Common Rail Injection, EGR

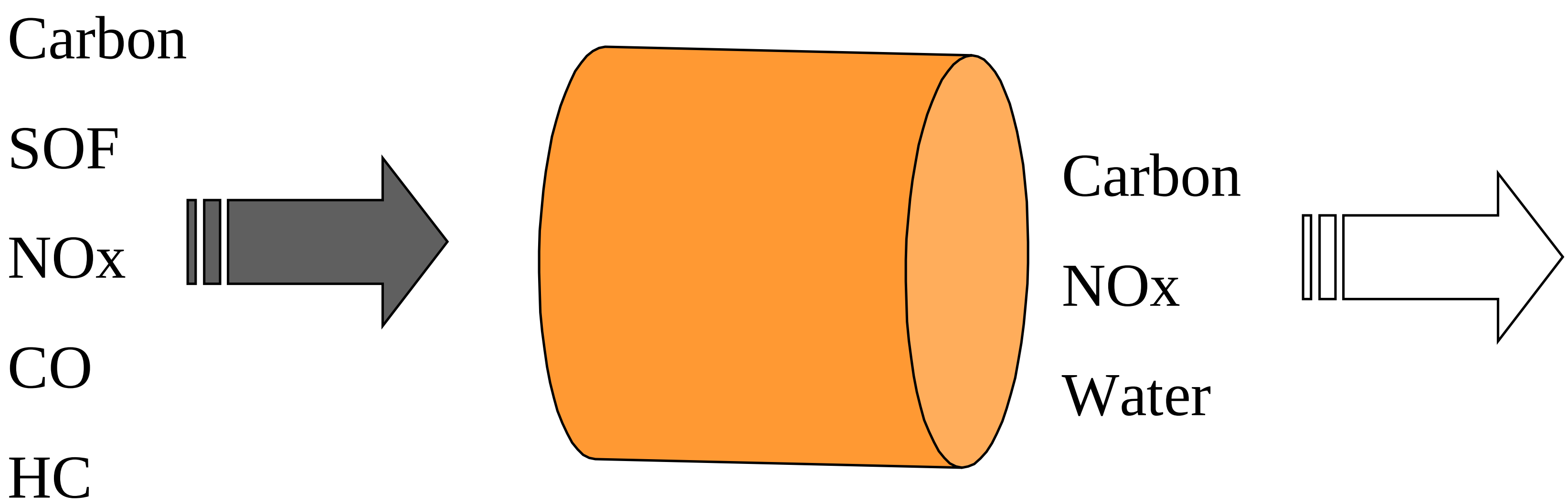
Technological Solutions (Cont.)

- Advanced Fuels
  - Low Sulfur, Other Properties (Reductants)
- Integrated Emission Control Will Allow Diesel Engines to Meet the Future Challenges

Light Duty vs. Heavy Duty Catalyst Operating Temperatures

- Light Duty
  - * LA-4 150-350C
  - * USO6 250-550C
- Heavy Duty
  - * Transient 180-450C
  - * Supp EURO III 300-430C

Diesel Oxidation Catalysts

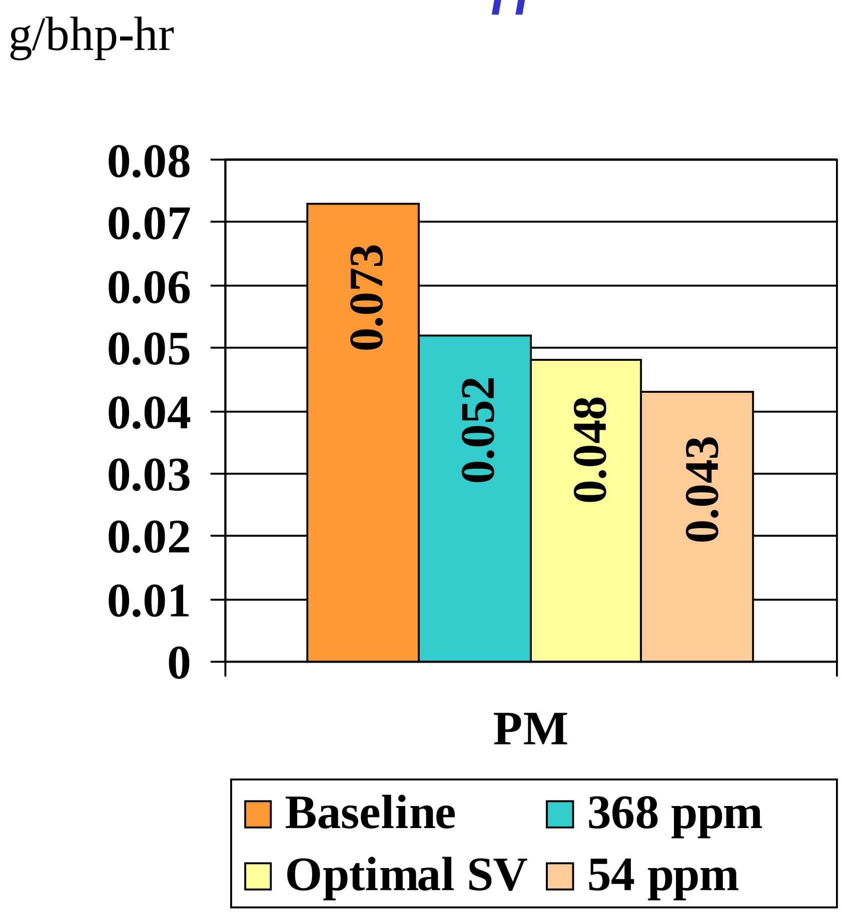


Oxidation Catalysts Oxidize CO, HC, and SOF to Reduce PM, CO, HC, and Toxic Emissions.

Diesel Oxidation Catalysts

- Oxidation Catalyst Control Capabilities
  - PM -- 20-50% Reduction
  - CO and HC -- >90%
  - Toxic HCs -- >70%
- Oxidation Catalyst Operating Experience
  - >5,000,000 Light-Duty Vehicles in Europe
  - >1.5 Million HDEs in the U.S.
  - >250,000 Nonroad Engines
  - Excellent Operating Experience

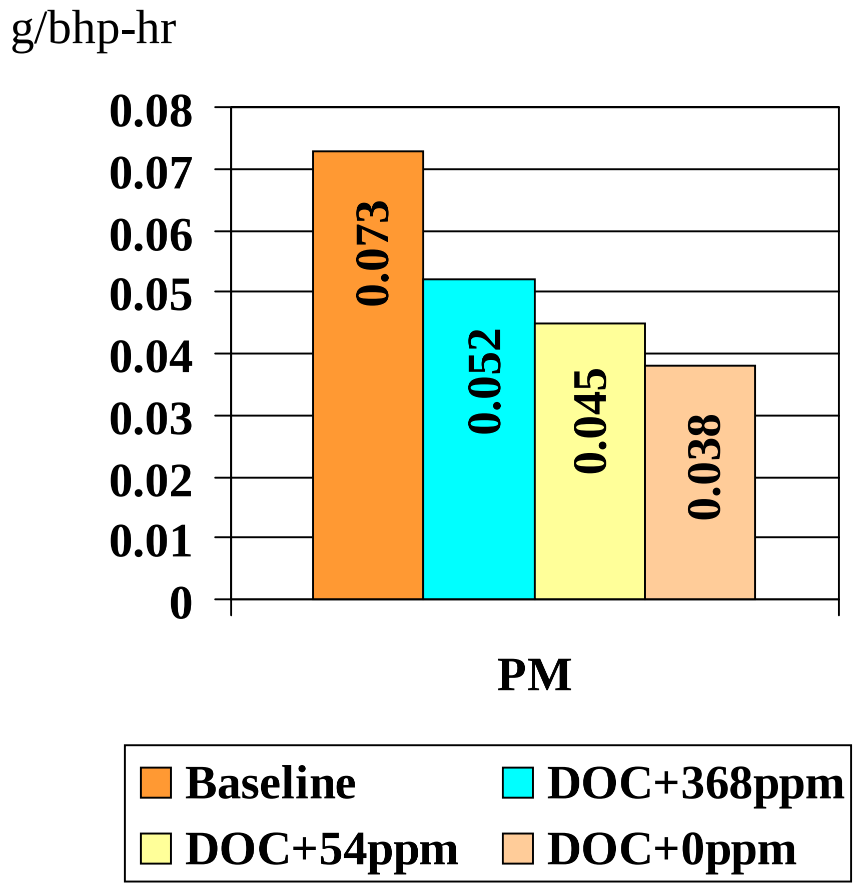
Diesel Oxidation Catalysts Are Proven Effective in Removing PM



- 0.05 g/bhp-hr PM Emissions Can Be Achieved on Both Fuels
- Significant Reductions in CO and HC Emissions Can Be Achieved

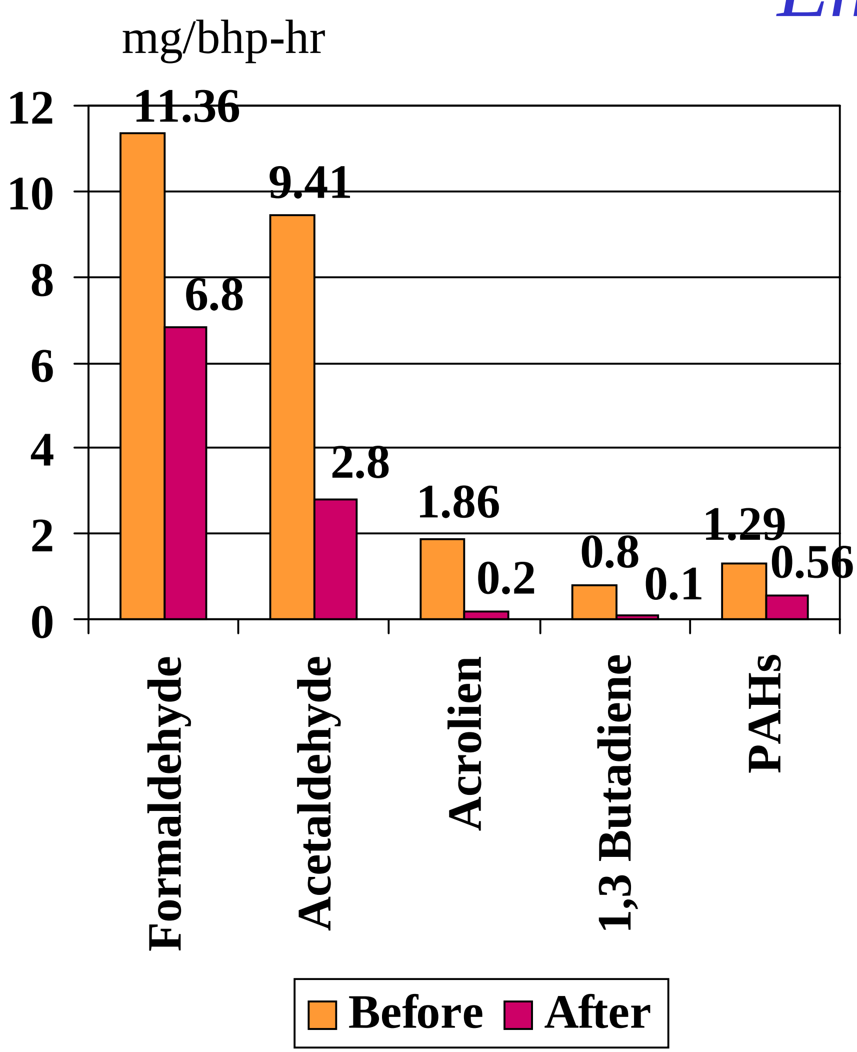
Source:MECA 1999

Diesel Oxidation Catalysts Are More Effective when Used With Low Sulfur Fuel



Source: MECA 1999

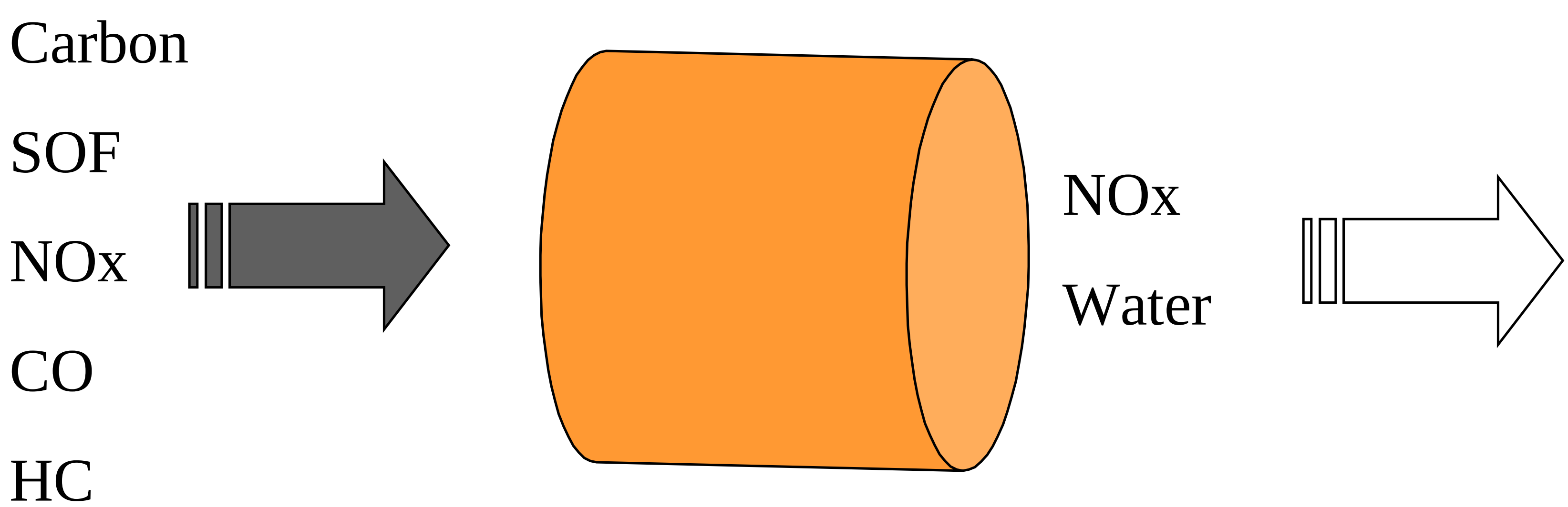
DOCs Destroy Large Fractions of Toxic Emissions



Source: MECA 1999

- Toxic Hydrocarbon Compounds Reduced by 68%
- PAH Emissions Reduced by 56%
- 368 ppm Sulfur Fuel

Diesel Particulate Filters

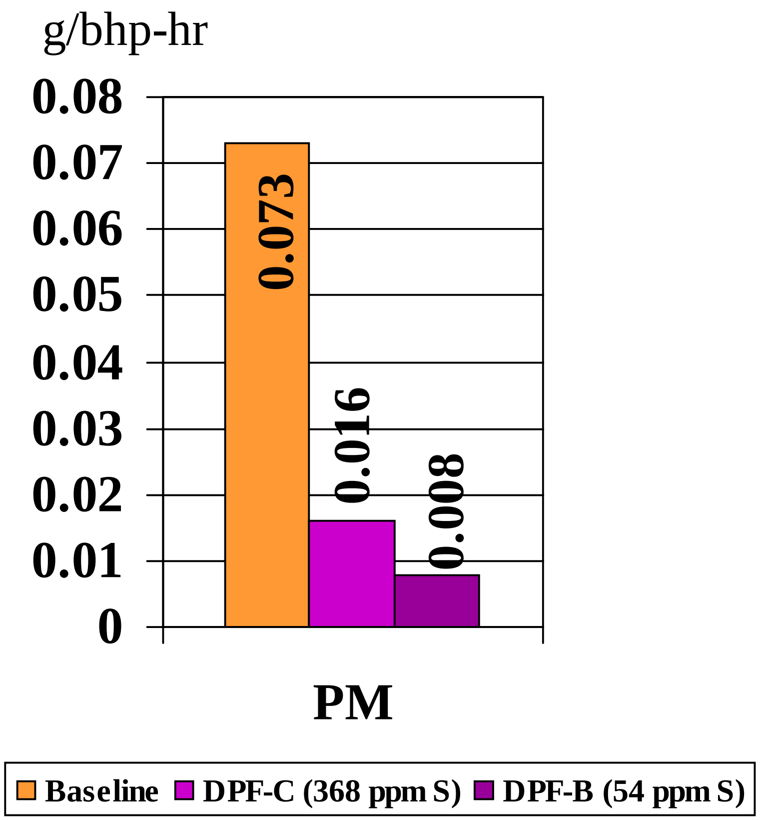


Diesel Particulate Filters Trap Carbon and Adsorbed SOF and Can Be Used to Oxidize CO, and HC to Reduce PM, CO, HC, and Toxic Emissions.

Diesel Particulate Filters

- Filter Control Capabilities
  - PM -- >90% Reduction
  - CO and HC -- >90%
  - Toxic HCs -- >90% Reduction
- Based Filter Operating Experience
  - Several Thousand Trucks and Buses in Commercial Operation in Europe
  - Demonstration Programs in Taiwan, Korea, Sweden, Germany, England, and Other Countries
  - Peugeot Will Offer Filter-Equipped LDVs in 2000
  - Over 10,000 Nonroad Engines Equipped

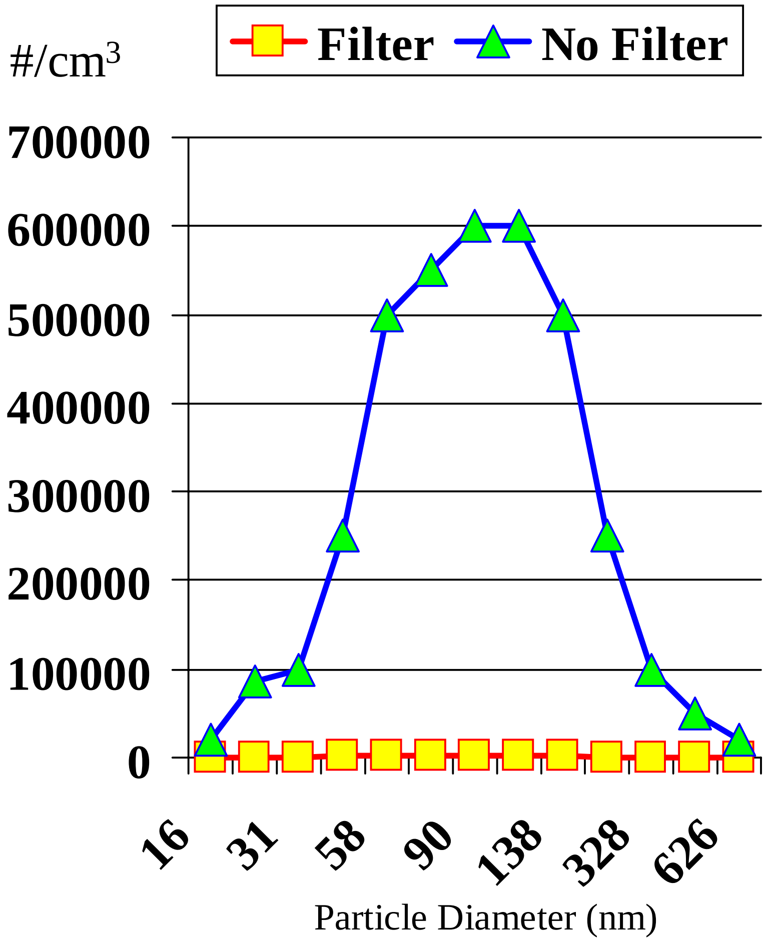
Diesel Particulate Filters Nearly Eliminate PM



Source: MECA 1999

- PM Emissions Well Below 0.02 g/bhp-hr Can Be Achieved on Both Fuels (0.008 with 54 ppm S Fuel)
- Significant Reductions in CO and HC Emissions Can Be Achieved

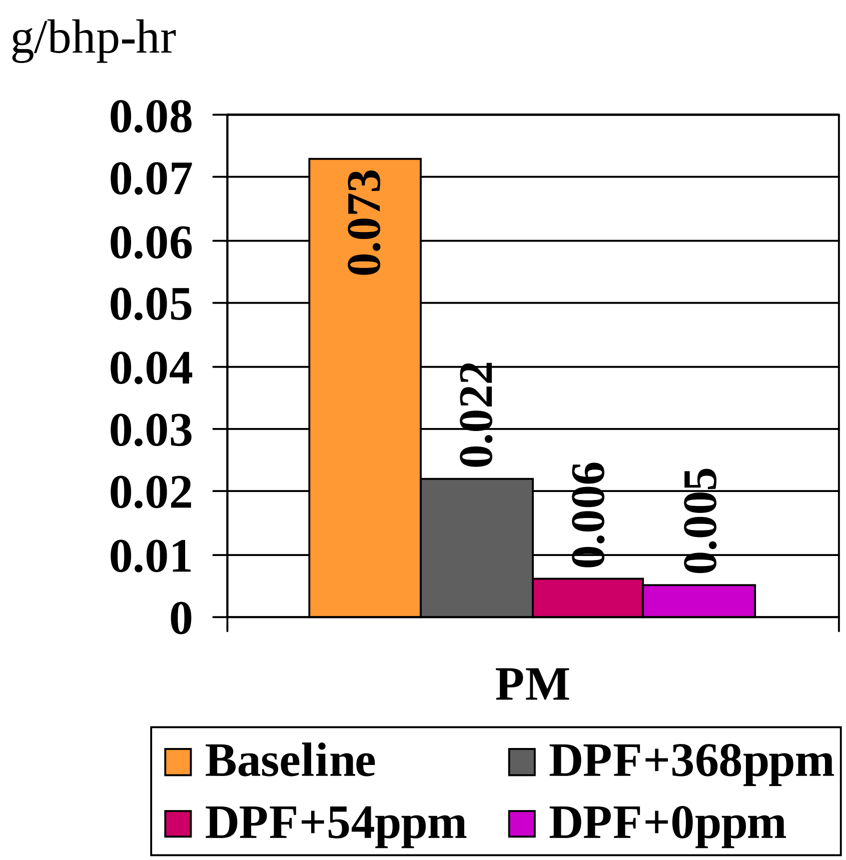
Filters Very Effective in Reducing Ultra-Fine Particles



Source: VERT 1998

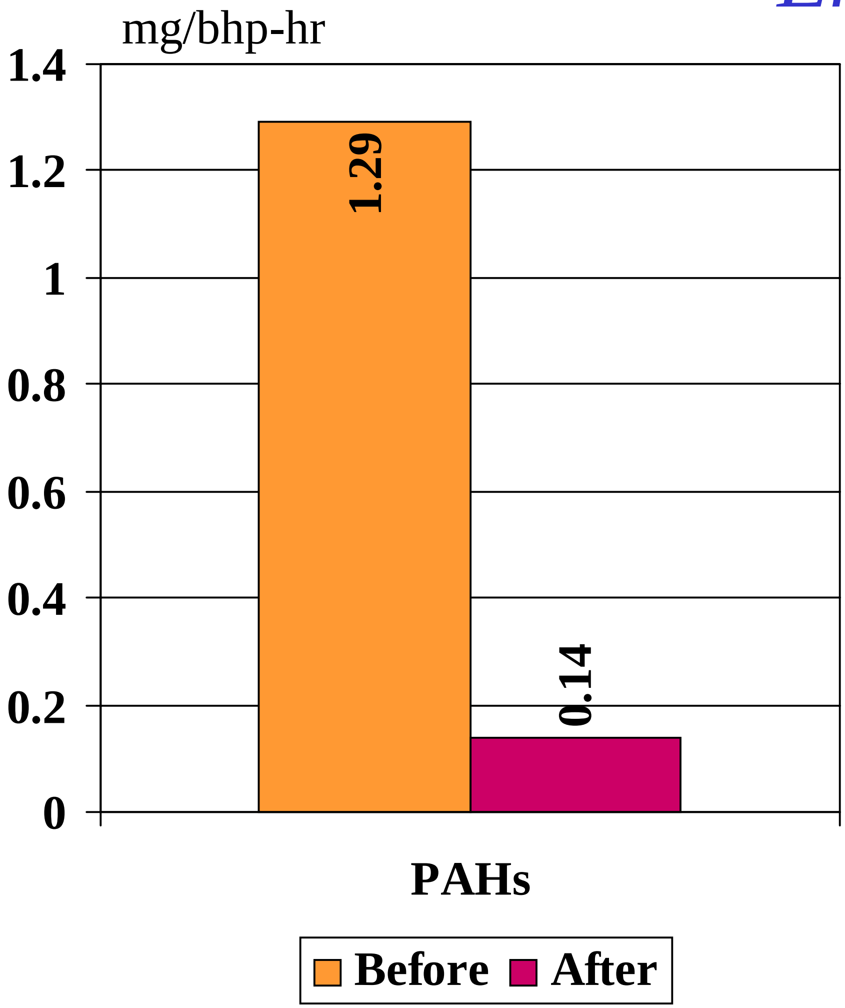
- Ultra-Fine Particles Reduced by in Excess of 99.99 %

Filters More Effective when Used With Low Sulfur Fuel



Source: MECA 1999

Filters Destroy Large Fractions of Toxic Emissions

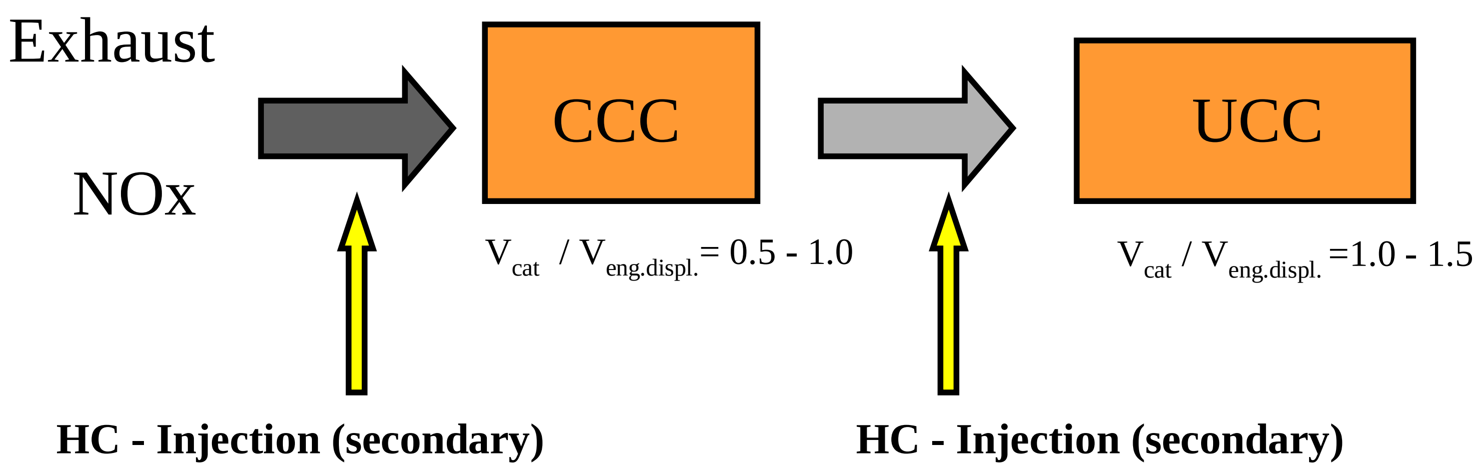


Source: MECA 1999

- PAH Emissions Reduced by 89%

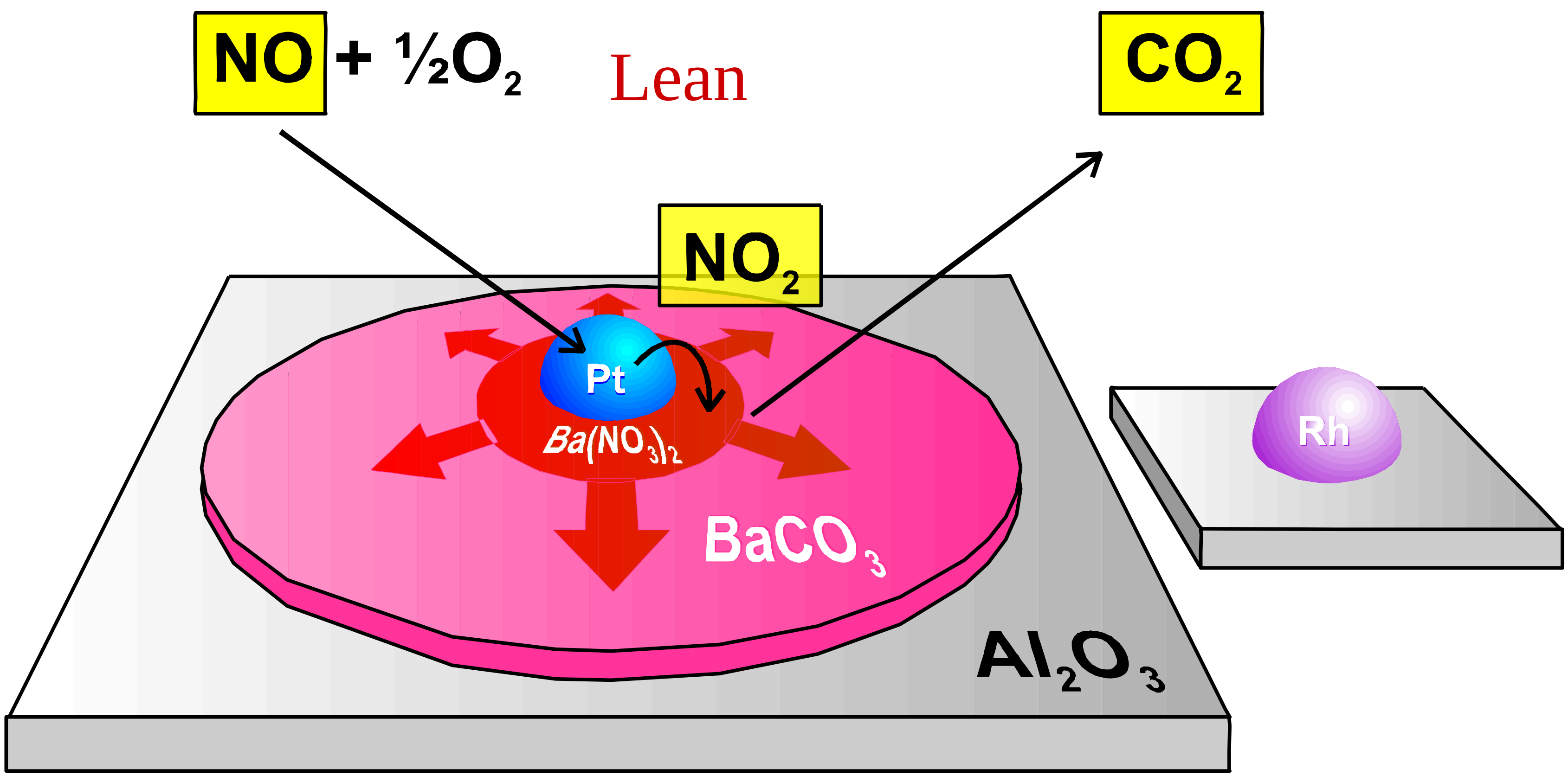
NOx Abatement Strategies for Diesel Engines

Active HC-DeNOx-System

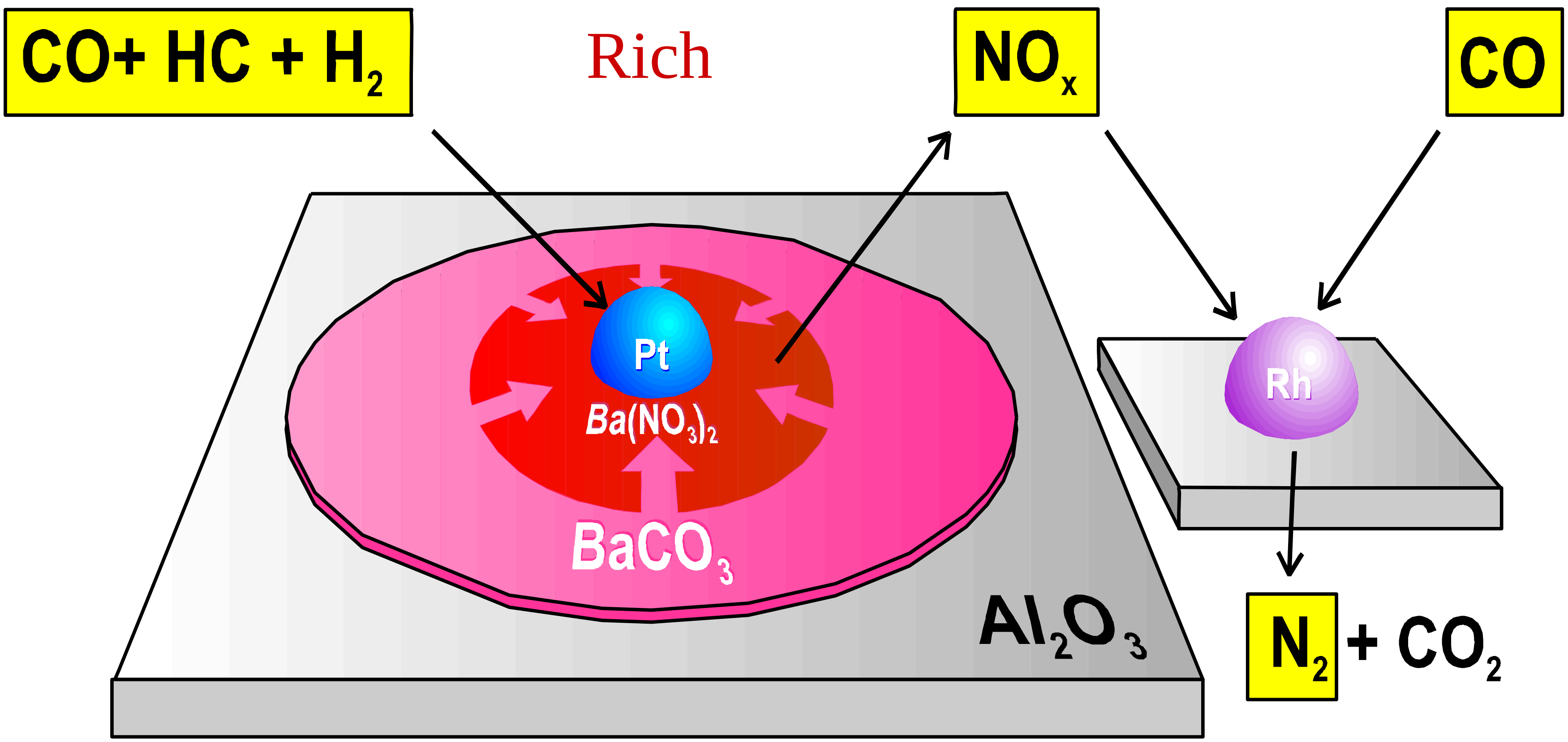


NOx Emissions Are Reduced in Two Steps By Up To 50%

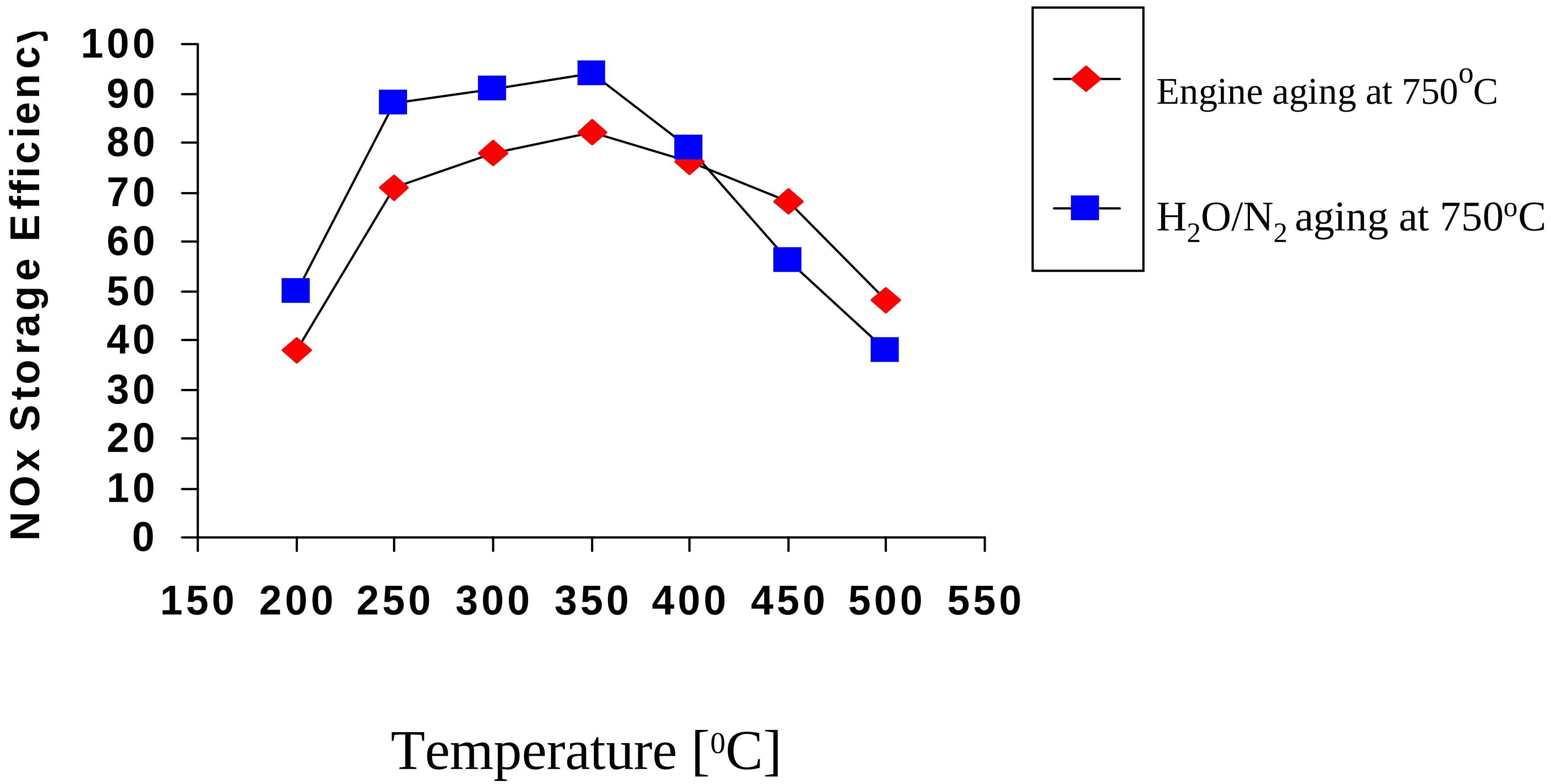
NOx Traps



NOx Traps

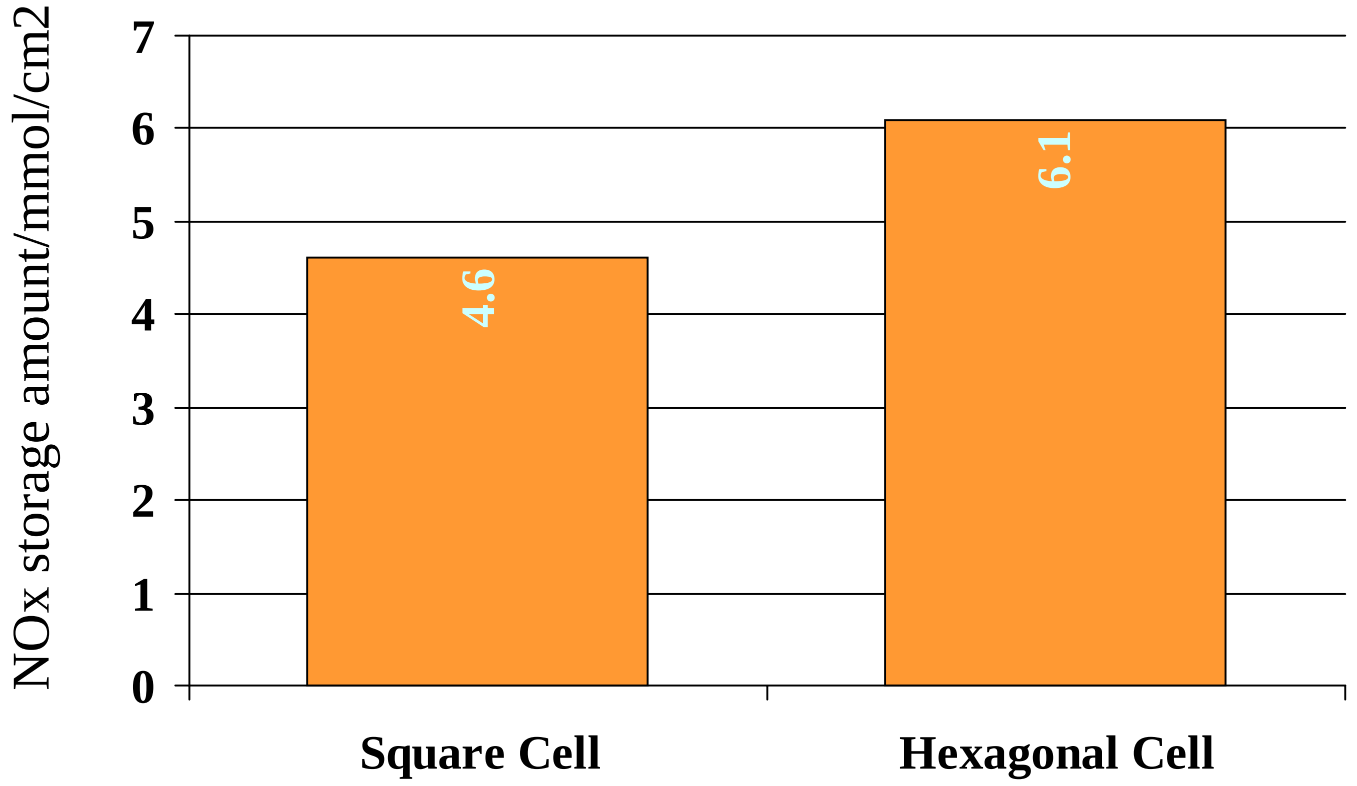


NOx Storage Efficiency



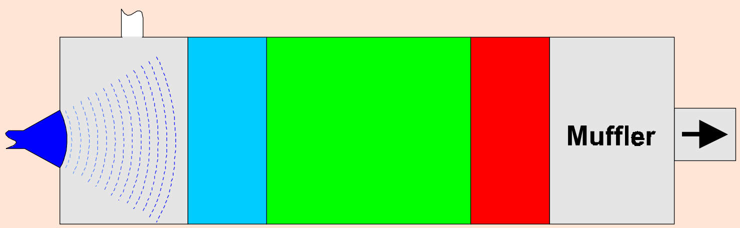
Source: MECA 1999

Cell Geometry Has A Positive Impact on NOx Storage



Source: SAE 1999-01-1279

Urea-SCR Catalyst System



Primary Function
Secondary Function

Hydrolysis Catalyst

Ammonia Generation:
$OC(NH_2)_2 + H_2O$ -------> $CO_2 + 2\ NH_3$

SCR - Denox Catalyst

Selective NOx - Reduction:
$4\ NO + 4\ NH_3 + O_2$ -----> $4\ N_2 + 6\ H_2O$

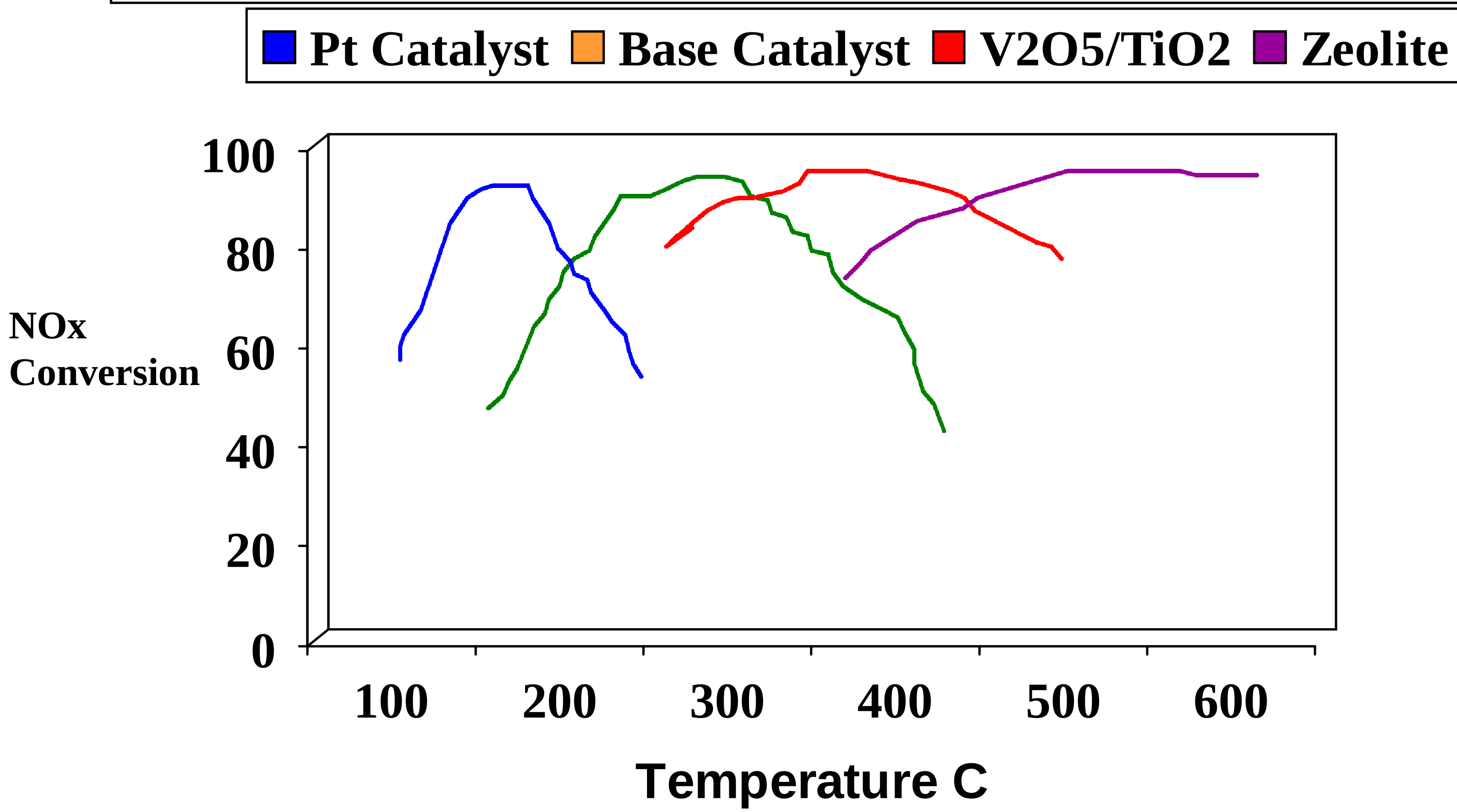
$HC + O_2$ ----> CO (1/3) + CO2 (2/3) + H_2O

Oxidation Catalyst

Ammonia Blocking (anti slip):
$4\ NH_3 + 3\ O_2$ -----> $2\ N_2 + 6\ H_2O$

$2\ CO + O_2$ ----> $2\ CO_2$

SCR Temperature Window



PLASMA-ASSISTED CATALYTIC NOx REDUCTION SCHEME

Plasma Generated High Energy Electrons

Catalyst

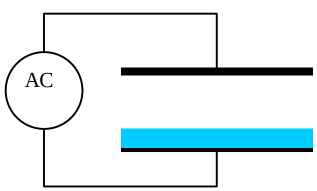
$$2NO + 4e + 4H^+ \rightarrow N_2 + 2H_2O$$

♦ Potential Reductions

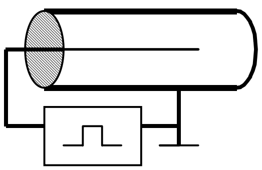
- NOx and PM Reductions Up to 80% in Laboratory Environment Have Been Reported
- Must Be Controlled to Prevent Undesirable Byproduct Formation (e.g. N_2O)

Plasma Reactor Types

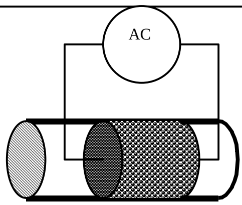
- Electron Beam
- Microwave
- High Frequency (1kHz) Pulsed Corona Discharge
  * Can Be Used in Gas Phase
- Dielectric Barrier Discharge
  * Based on O_3 Generator Technology
  * Dielectric Barrier (Al_2O_3) Charges and Extinguishes Discharge
- Packed Bed
  * Material with High Dielectric Constant and Ferro-Electric Properties



Dielectric-barrier discharge



Pulsed corona



Electrified packed bed

NOx Technology Concepts Overview

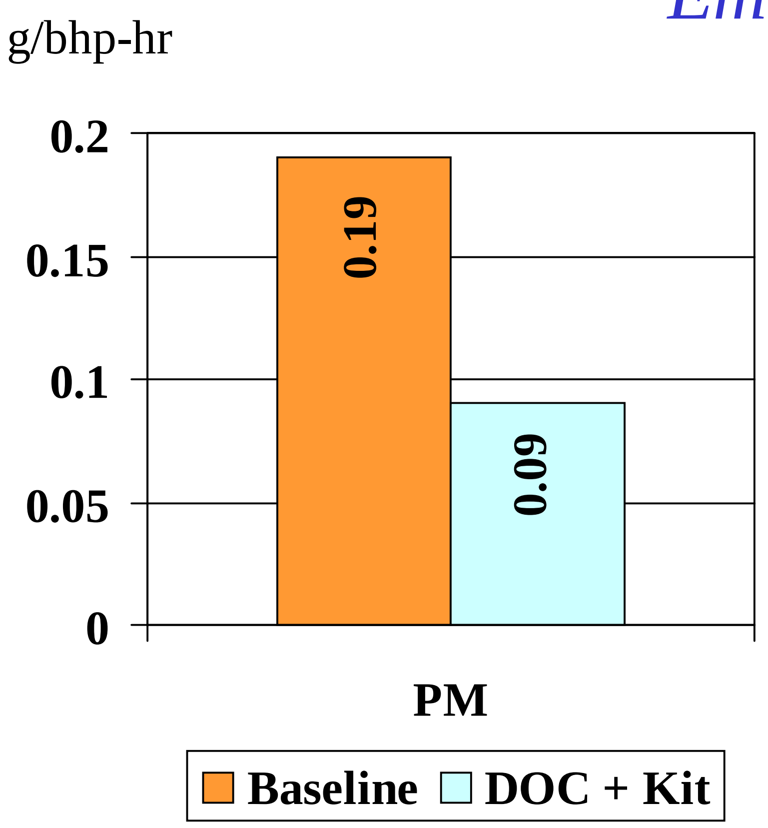
Technology	Performance Range				Potential Commercial Availability
	NOx	CO	HC	PM	
Active Lean NOx	25-50	>70	>70	~ 30	2000
NOx Adsorber	50-70	>70	>70	> 30	2004
SCR Urea	>80	>50	>70	$\geq$ 30	2000
Compact SCR	>90	>70	>70	$\geq$ 30	2004
Plasma / NOx Cat.	>65	>50	>50	~ 30	Post - 2004

NOx Technologies Operating Experience

- Passive Lean-NOx Catalysts Used on PC in Europe
- NOx Adsorbers Have Been Used in Vehicle Trials
- SCR Used on Stationary Sources, Marine Vessels, Locomotives and Have Been Used in Truck Demonstration Programs
- Plasma Technology Is in the Laboratory Stage

Examples of Integrated Systems

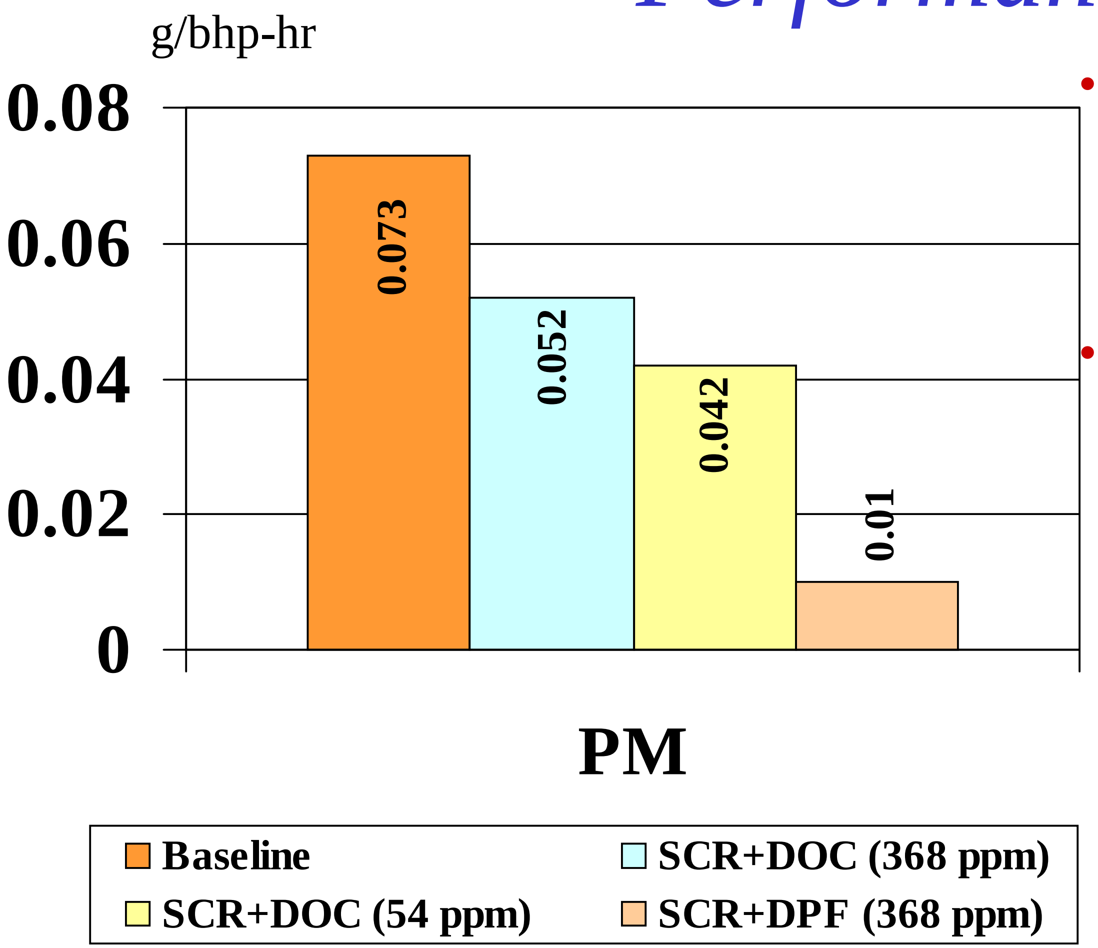
Diesel Oxidation Catalysts Combined with an Electrically-Powered Supercharger Reduce PM Emissions



- A 50 % Reduction in PM Emissions Can Be Achieved

Source: MECA 1999

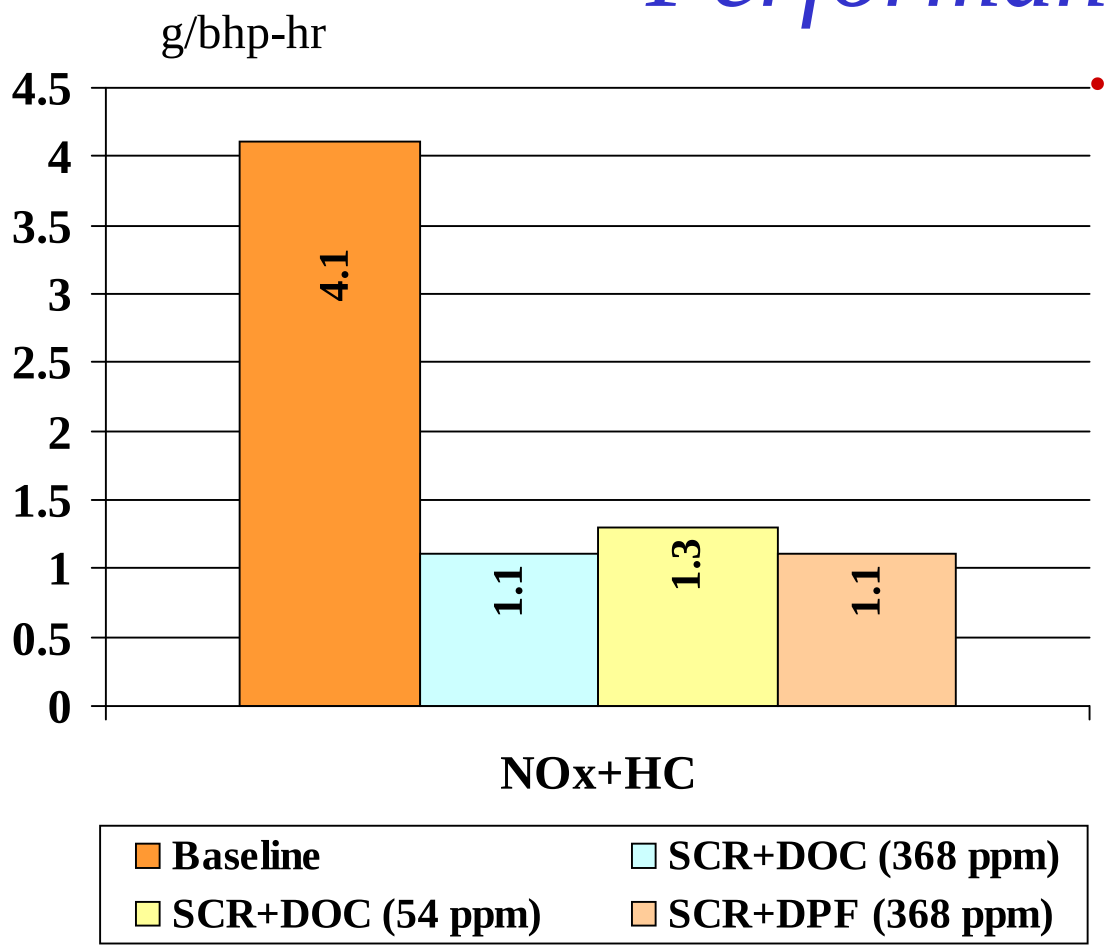
SCR With DOC and DPF Performance



- PM Emission Levels Below of 0.01 g/bhp-hr with DPF Technology using 368 ppm S fuel
- PM Emissions less than 0.05 g/bhp-hr Can Be Achieved with DOC Technology and 54 ppm S Fuel

Source: MECA 1999

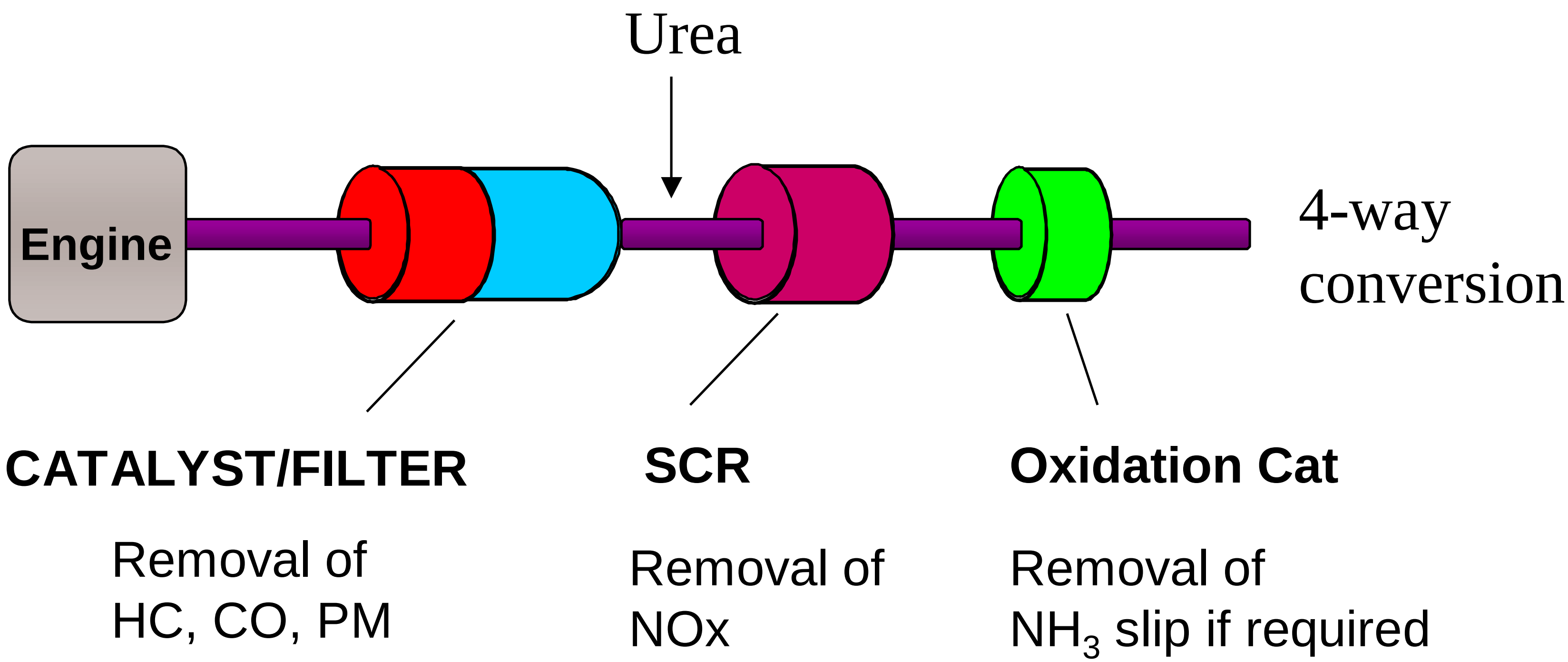
SCR With DOC and DPF Performance



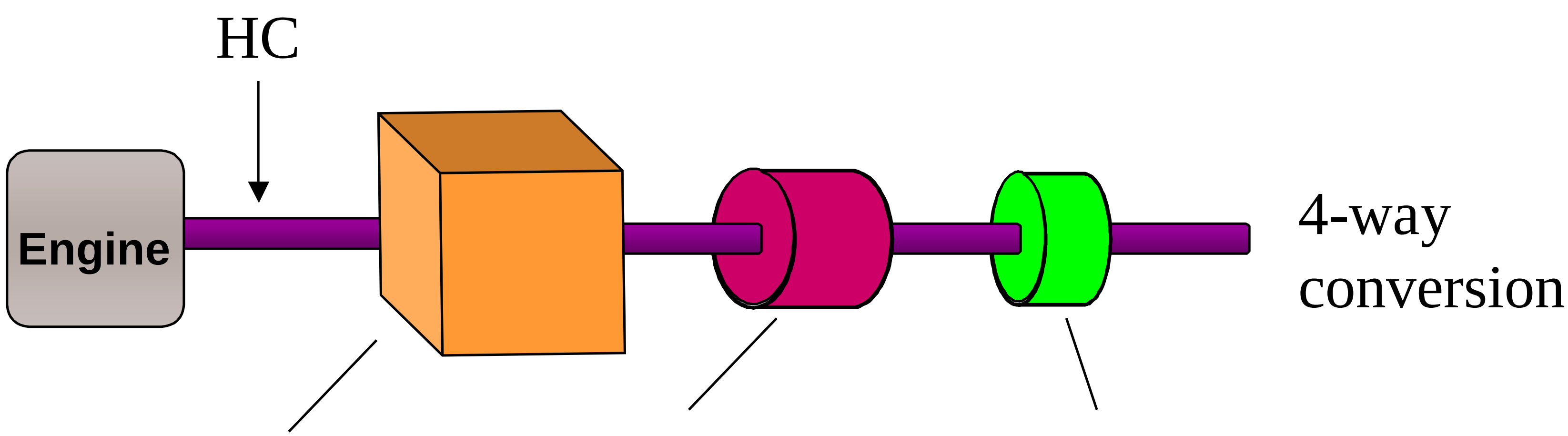
- Combined with the Low PM Emissions, NOx + HC Levels Below1.5 g/bhp-hr NOx Can Be Achieved on 368 ppm S Fuels

Source: MECA 1999

System Configuration No.1



System Configurations No.2



Heat Exchanger

Enhances Catalyst Performance

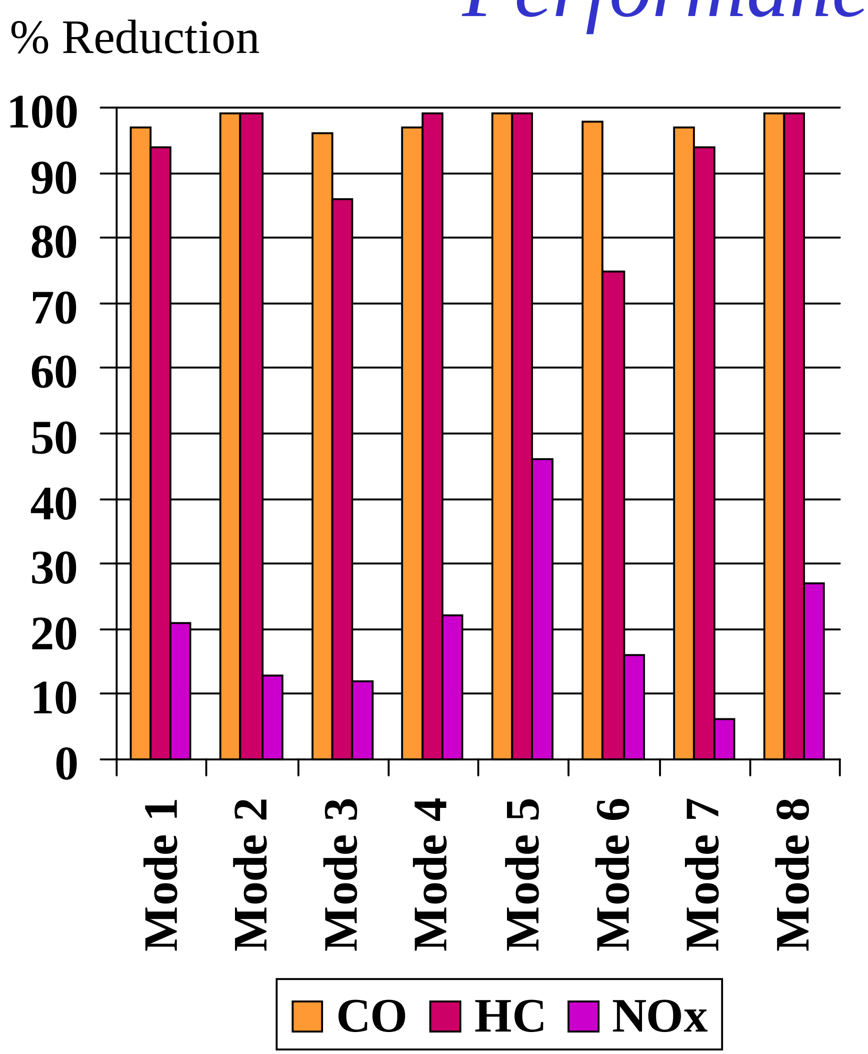
Lean-NOx

Removal of NOx

Catalyst/Filter

Removal of HC, CO, PM

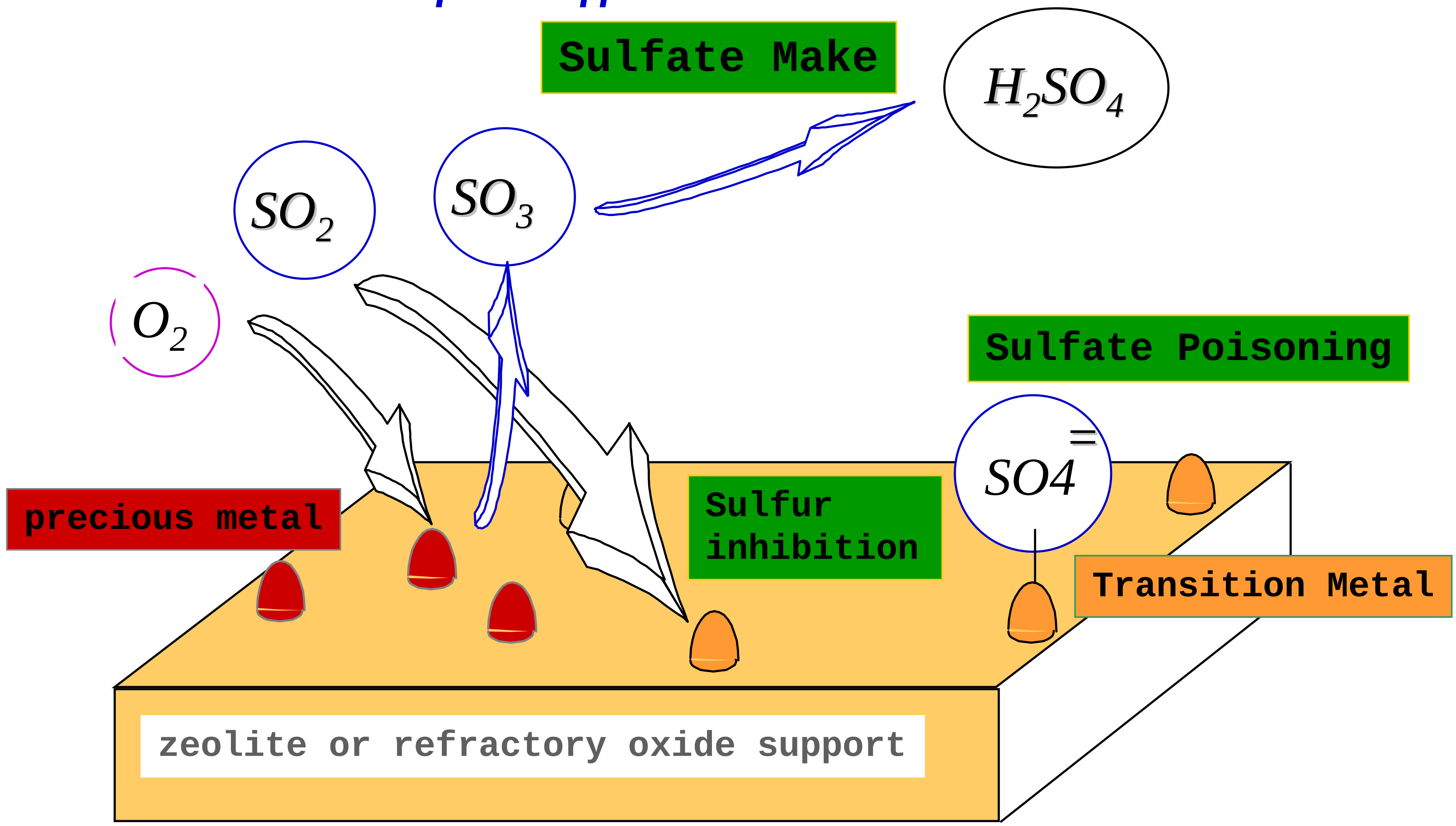
Performance of System No.2



Source: SAE Paper 1999-01-2924

- Reductions in CO, NOx, and HC Were Achieved

Sulfur Effects



Summary of Influence of Fuel Sulfur on Diesel Exhaust Emission Control Devices

Control Technology	Sensitivity to Sulfur
Oxidation Catalyst	Moderate
Lean NOx (DeNOx) Catalyst	Moderate to Extremely High
SCR with Urea	Low, but May Require Oxidation Catalyst for NH_3 slip
Catalytic Particulate Filters	Moderate
Particulate Filters with NOx Conversion Catalyst	High When Diesel Fuel Sulfur Exceeds 50 ppm
Non-Thermal Plasma	Thought to be Low
NOx Adsorbers	Extremely High (near zero may be necessary)

Note: To meet upcoming particulate and NOx emission levels and beyond, combinations of devices may be required

Sulfur Effects – Other Issues

- Off-Cycle Emission Test Points
- Increase the Number of Applications for Some Technologies
- Maximum Performance for Catalyst-Based Technologies
- Technologies May Be Used in Combination

Conclusions

- Further, Significant Diesel Emission Reductions Are Possible for Both Onroad and Nonroad Vehicles

- Exhaust Emission Controls Are Currently a Largely Untapped Source for Significant Emission Reductions (Simultaneous PM, Toxic HC, and NOx Control)

- NOx Abatement Technologies are Advancing and Several Control Strategies Are Expected to Be Available in the 2004 Time Frame

- Ultra-Low Sulfur Fuel Would Open Significant Additional Opportunities for the Control of Diesel Emissions

- A Truly Clean Diesel Will Require Advanced Engine Design, Integrated Emission Control Technology, and Clean Fuels