Emission Control Systems for NO_x and PM: Beyond the 2010 Standard

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EMISSION CONTROL TECHNOLOGIES

Outline of the Presentation

Diesel Engine Emissions and Global Regulations

Emission Control Components
- DOC
- DPF
- SCR

Current SCR Technologies
- SCR for Euro IV/V
- SCR for Euro VI/US 2010
- Non-road Systems

Future Regulations

Future Technology Trends
- Next generation of SCR catalysts
- Capabilities of, and Challenges with, the SCRF® Component
- Low Temperature NOx Storage and Release: the dCSC™ Component
- Ammonia Availability at Low Temperature
- System Strategies

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Diesel Engine Emissions

Diesel Engine Emissions:

- CO, HC, **NO_x**, SO_x
- **Particulate Matter** (PM)

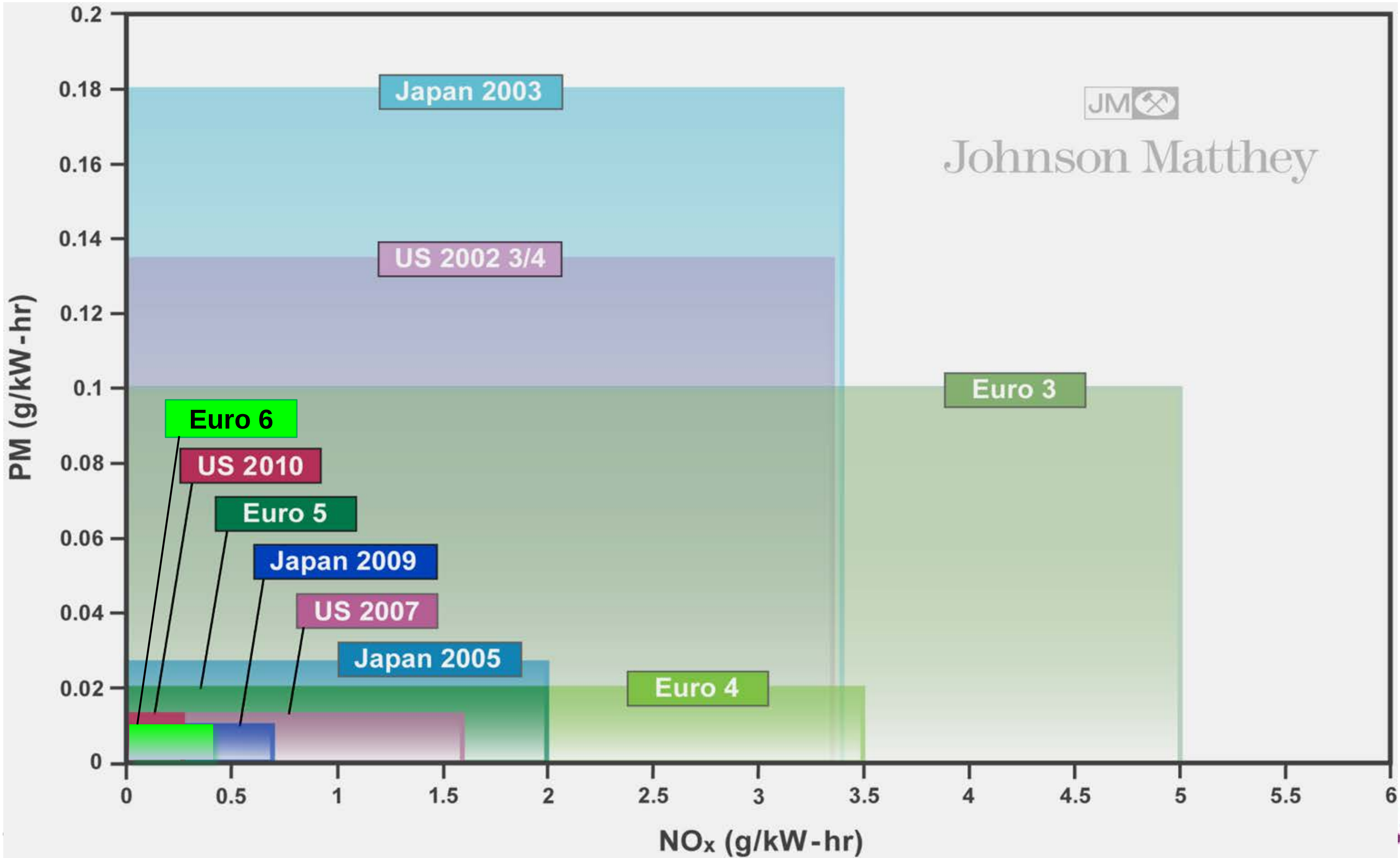
Emissions lead to:

- photochemical smog (sunlight + HC + NO_x)
- acid rain (water + NO_x, SO_x)
- health effects (PM + NO_x)

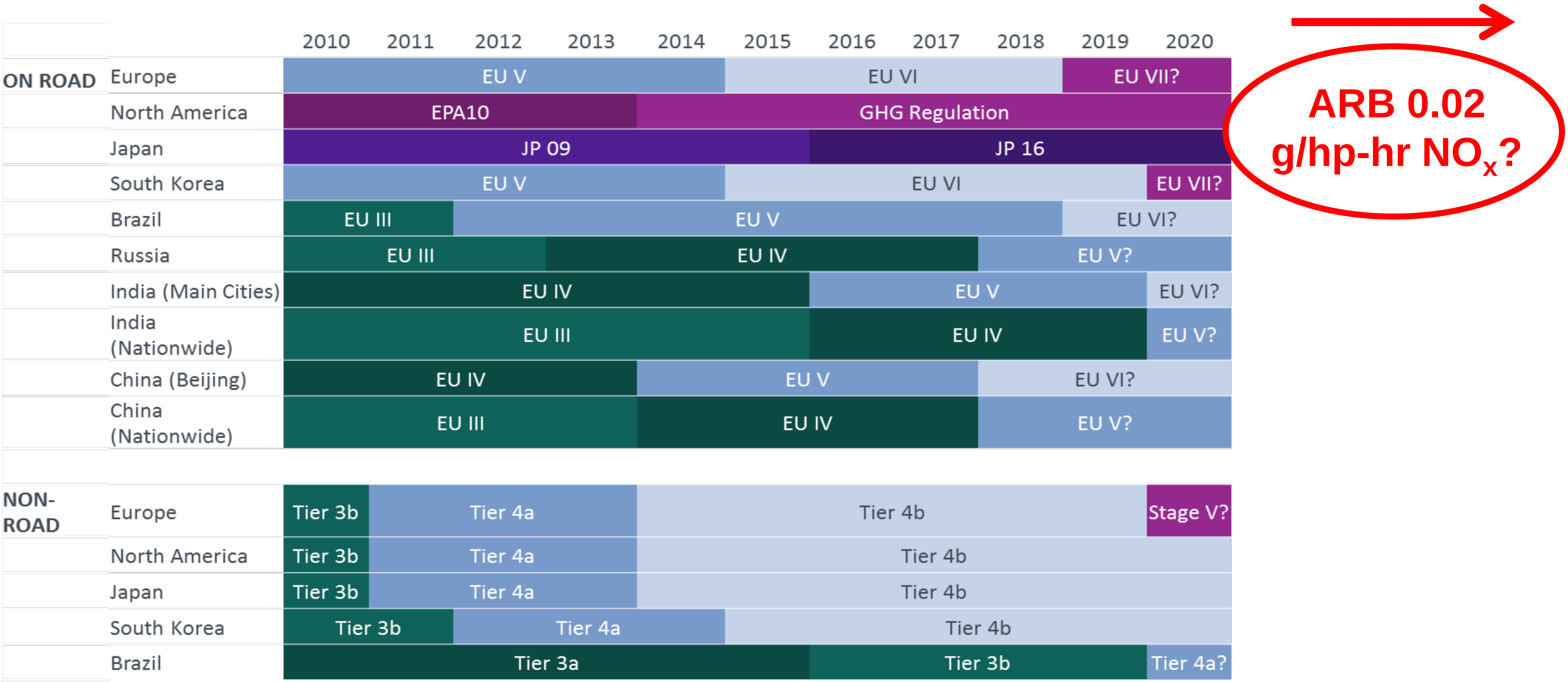
Pollutants are created in the on-road sector as well as in the non-road sector due to the benefits and high usage of diesel vehicles and equipment

Global HDD On-Road Emission Regulations

Regulations forcing both PM and NO_x emission control from new engines



Heavy Duty Diesel - Global Regulations



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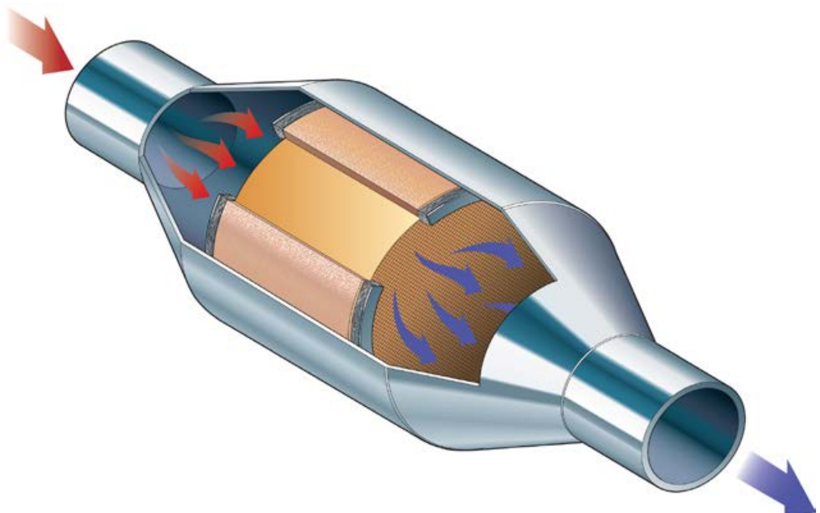
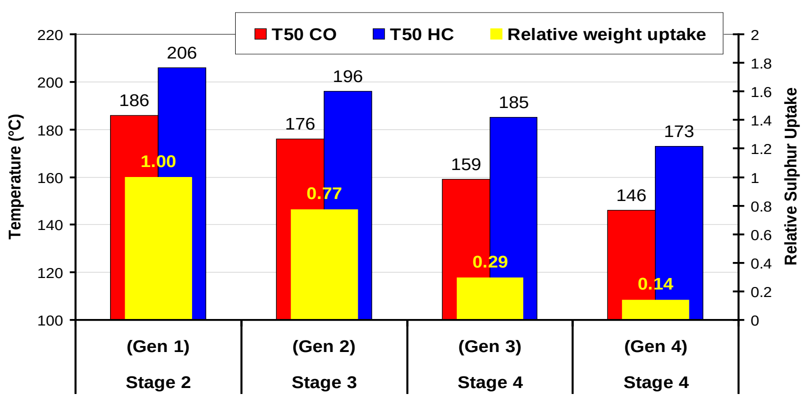
PM Control by Diesel Oxidation Catalyst (DOC) 20 – 50%

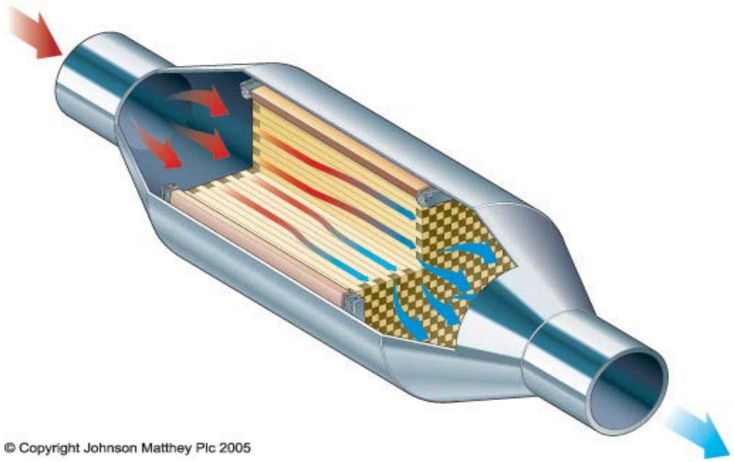


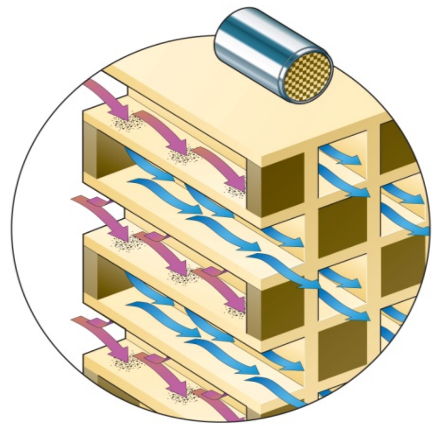


- To reduce exhaust CO, HC and PM emissions from diesel engines
- To oxidize NO into NO_2 to burn PM when it is placed in front of DPF
- To burn fuel injected across the DOC to generate an exotherm for active regeneration of PM when placed in front of a DPF (DEC use)
- PGM content can be Pt or Pt/Pd

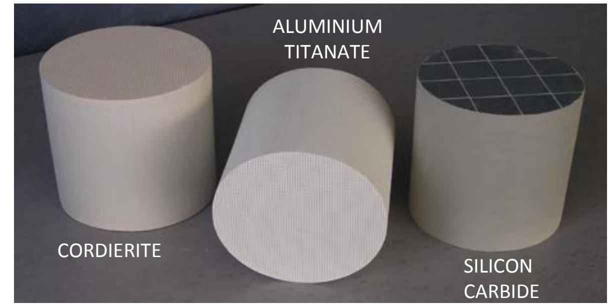
PM and PN Control by Catalyzed Soot Filter (CSF) >90%

CSF



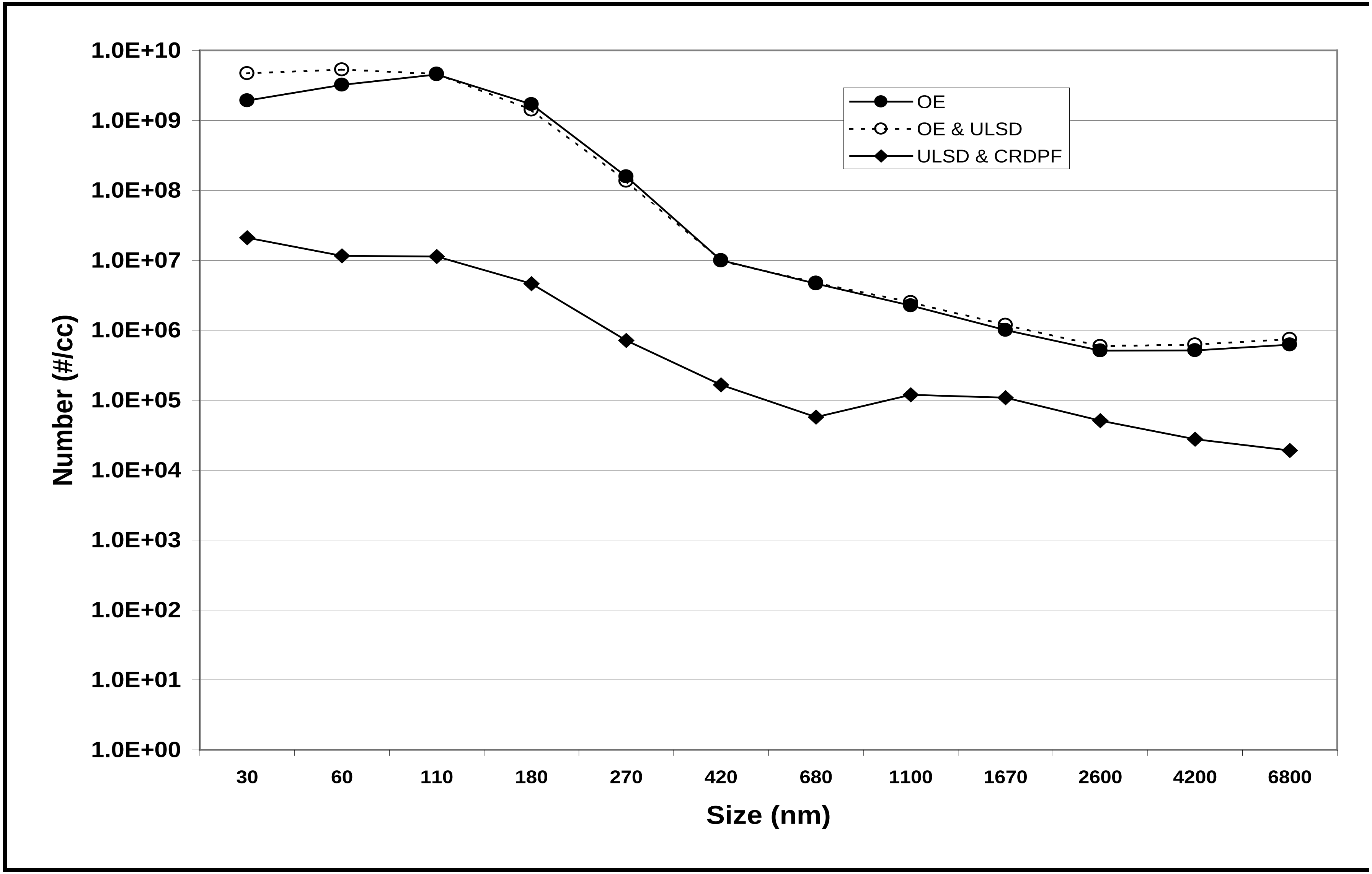


Particulate filtration



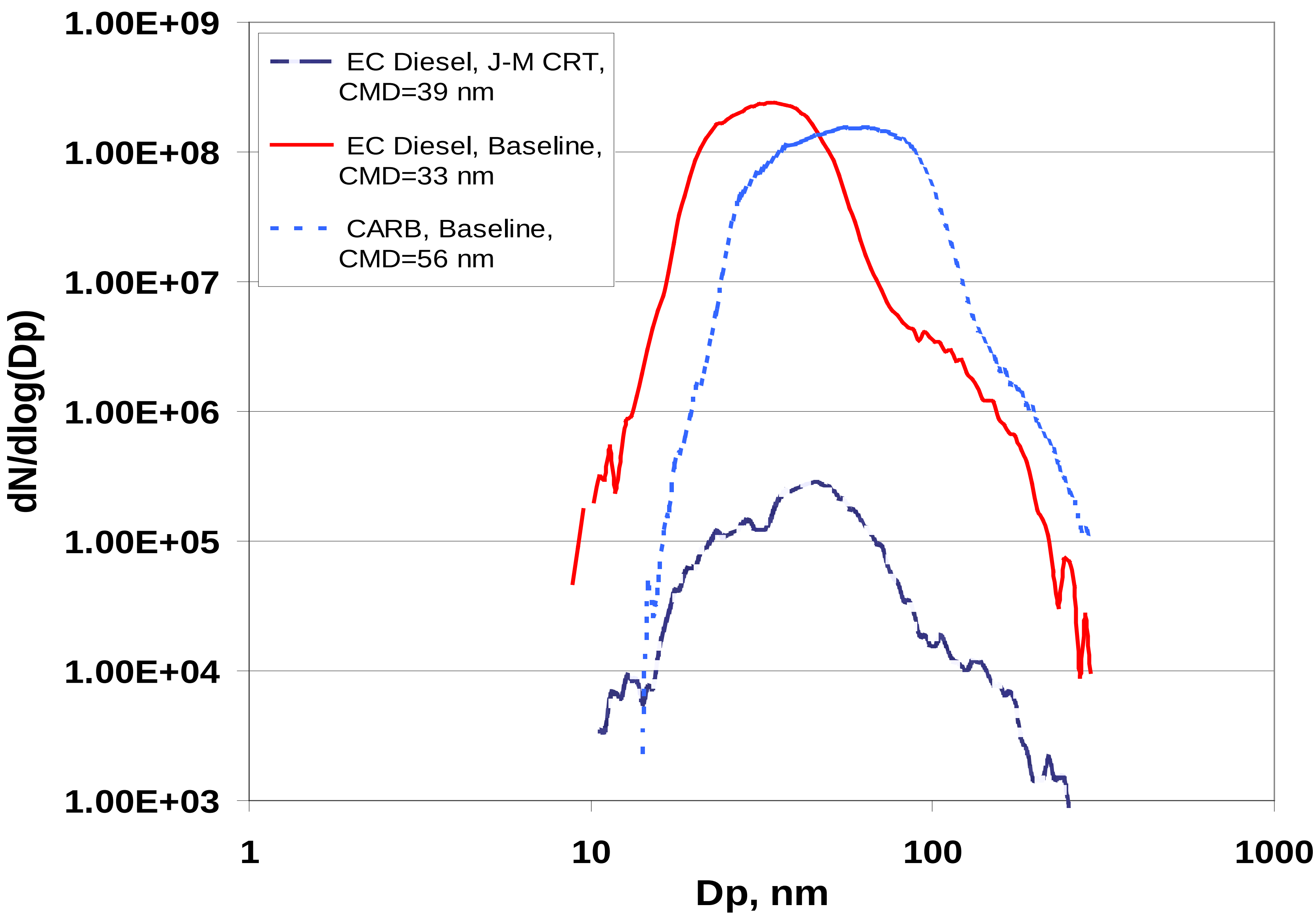
- An oxidation catalyst coated onto a diesel particulate filter
- CO, HC and PM emissions are removed under normal conditions
- NO_2 is produced which helps to keep the filter clean via the CRT® effect
- Periodic filter cleaning events (active regeneration) require the coating to oxidize injected fuel to obtain temperatures over 600°C
- All types of filter can be coated with Pt or Pt/Pd

Particle Sizing with CRT Filter on Ser 50 Engine
NY City Transit Bus under CBD Cycle



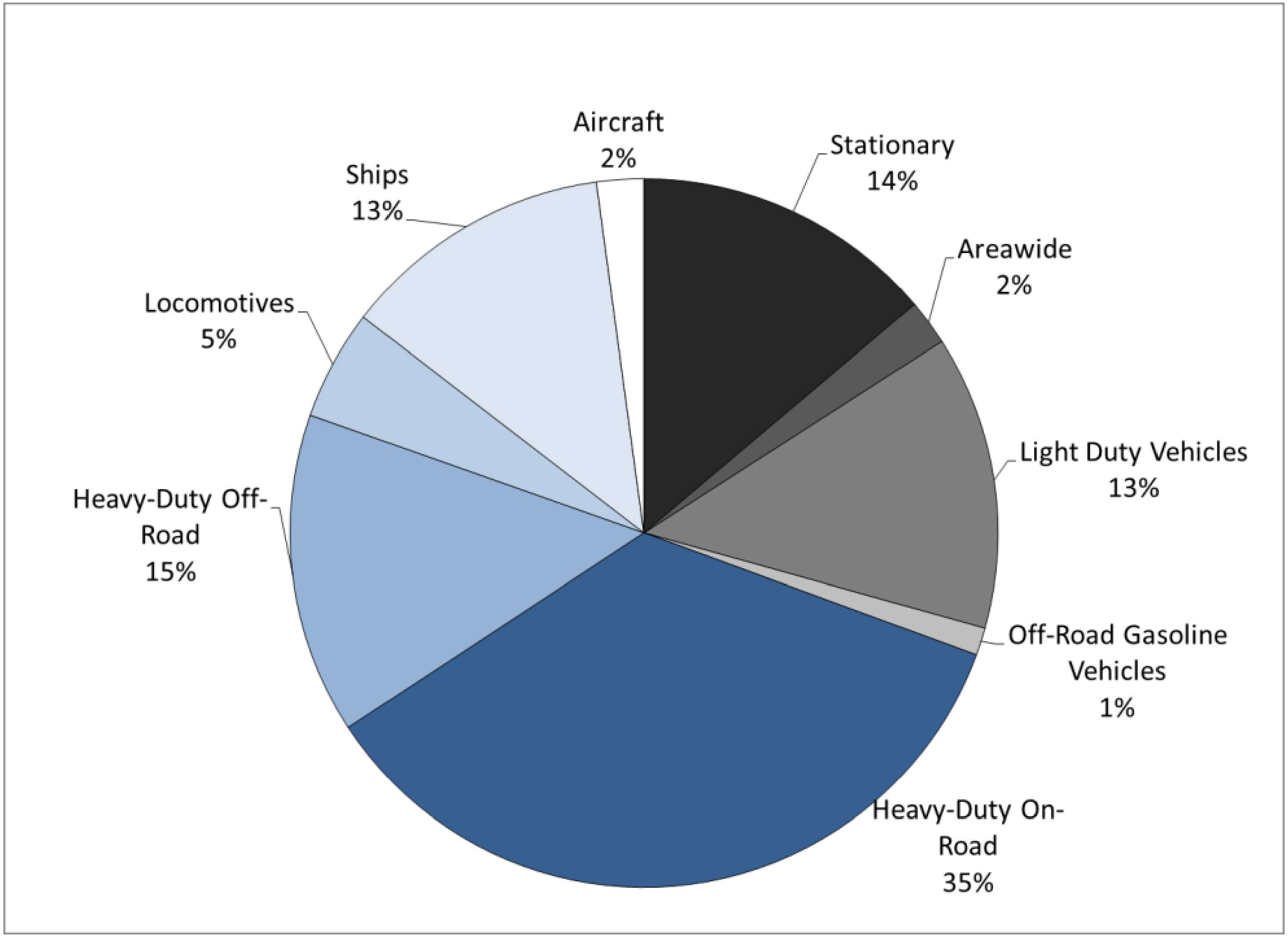
Particle Sizing with CRT Filter on DDC Ser 60 Engine

Class 8 Truck under SS Cycle



Contributions to NO_x Emissions in California

Source: CARB Heavy Duty Technology & Fuels Assessment – 2015 - DRAFT



Selective Catalytic Reduction (SCR)

Effective NOx Control Technology

Use ammonia (NH_3) to reduce NO_x to N_2 under oxidizing conditions

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

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

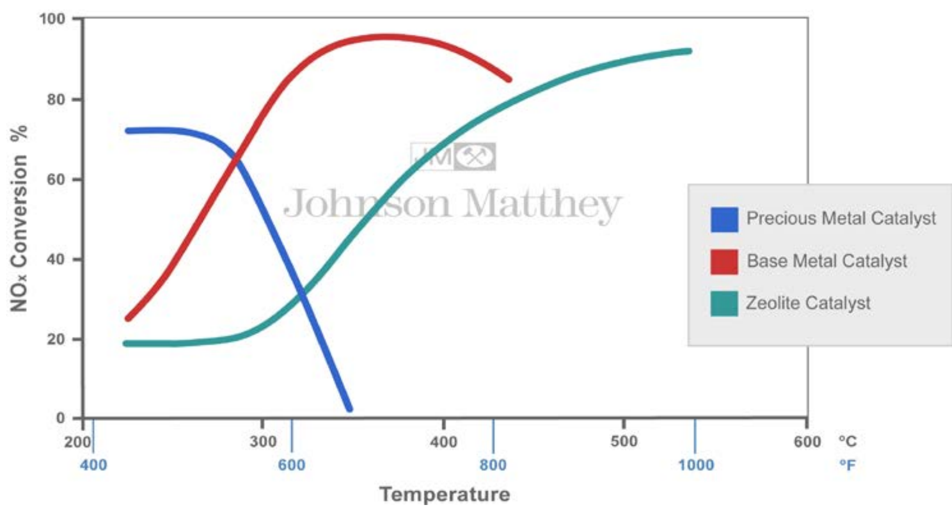
NO_2 promotes SCR activity; pre-DOC helps:

$$\mathbf{2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O}$$ **VERY FAST REACTION**

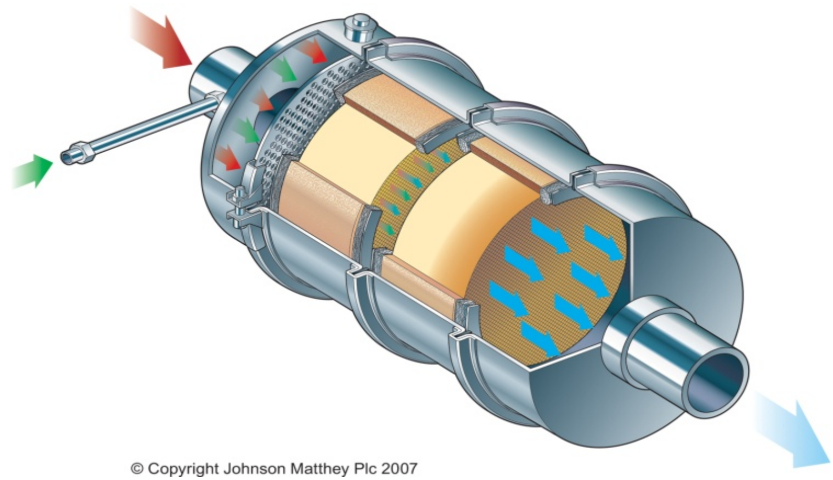
Ammonia can be derived from a number of sources (e.g. urea, ammonium carbamate, aqueous ammonia etc.)

Vanadium based catalysts mostly used (Euro IV), now zeolite based catalysts have been introduced for advanced markets (Japan 09 & US 10)

NO_x Control by Selective Catalytic Reduction (SCR)



SCR catalyst performance



SCR system with outlet slip catalyst zone

- Reduce NO_x to N_2 under high oxygen (lean) conditions. Extra reductant (usually urea) is injected into the exhaust upstream of the catalyst

- Base metal and zeolite-based catalysts offer the widest operating temperature window.

- Optional slip catalyst can be added downstream to remove unreacted reductant

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Euro IV/V: Primary Strategy SCR Only

May use ASC = Ammonia Slip Control Catalyst

Challenges for Euro IV

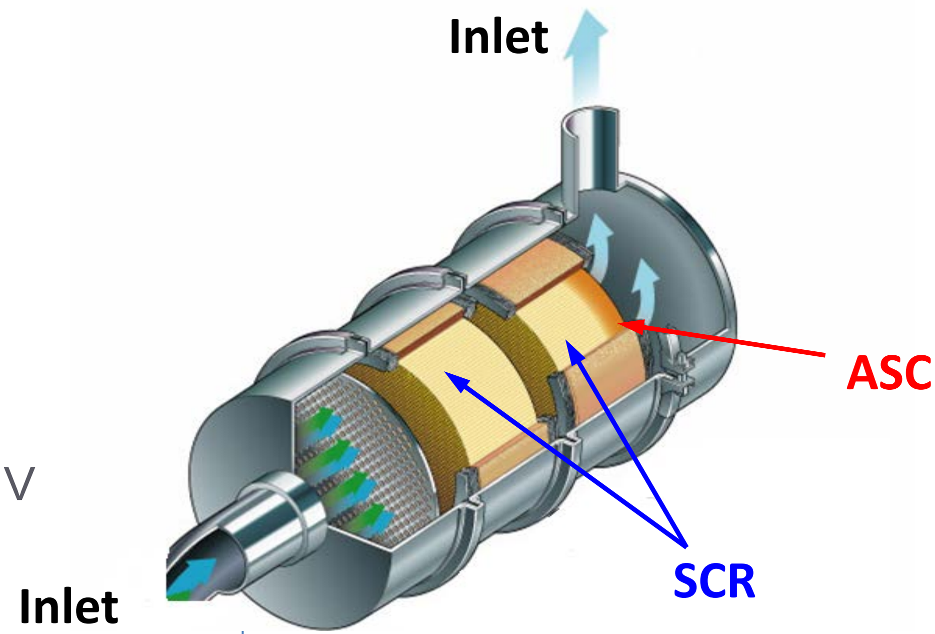
- 70% NO_x conversion
- PM met by engine
- Durability to high sulfur fuel (350 ppm)

Challenges for Euro V

- 85% NO_x conversion
- Less NH_3 slip requirement
- Retain similar SCR packaging as Euro IV

JM offers:

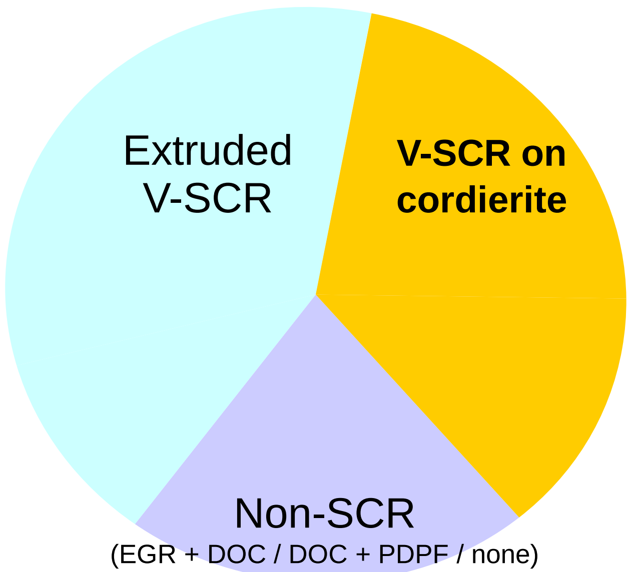
- Highly active Extruded V SCR
- Highly active Washcoated V SCR
- Combination of SCR with ASC
  - ➢ EU IV SCR + ASC allows higher urea dosing to meet EU V

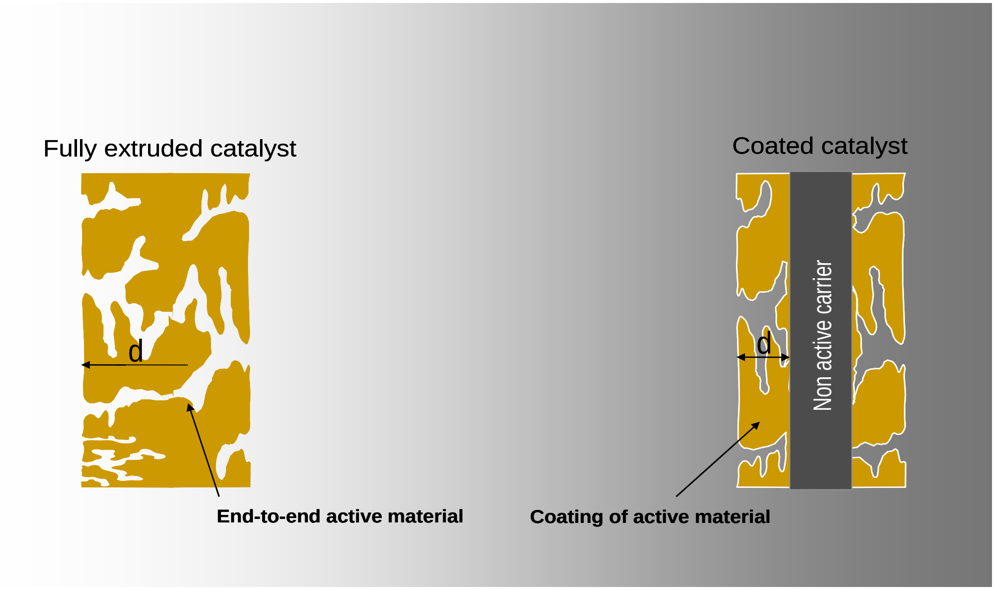


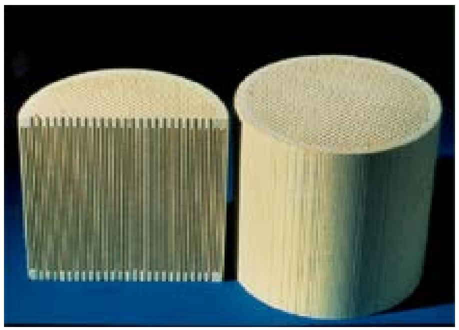
SCR + SCR//ASC (zoned coated)

Vanadium-SCR: Catalyst of Choice for Euro IV/V

JM Extruded and Coated V-SCR Well Proven Solutions







Current System Designs in the On-Road Market

Currently, the European, North American and Japanese regulations are all met using the same systems architecture:

DOC + CSF + SCR + ASC

DOC – Diesel Oxidation Catalyst

- Removes CO and HC
- Oxidises fuel to drive active filter regeneration
- Converts some NO into NO_2

CSF – Catalysed Soot Filter

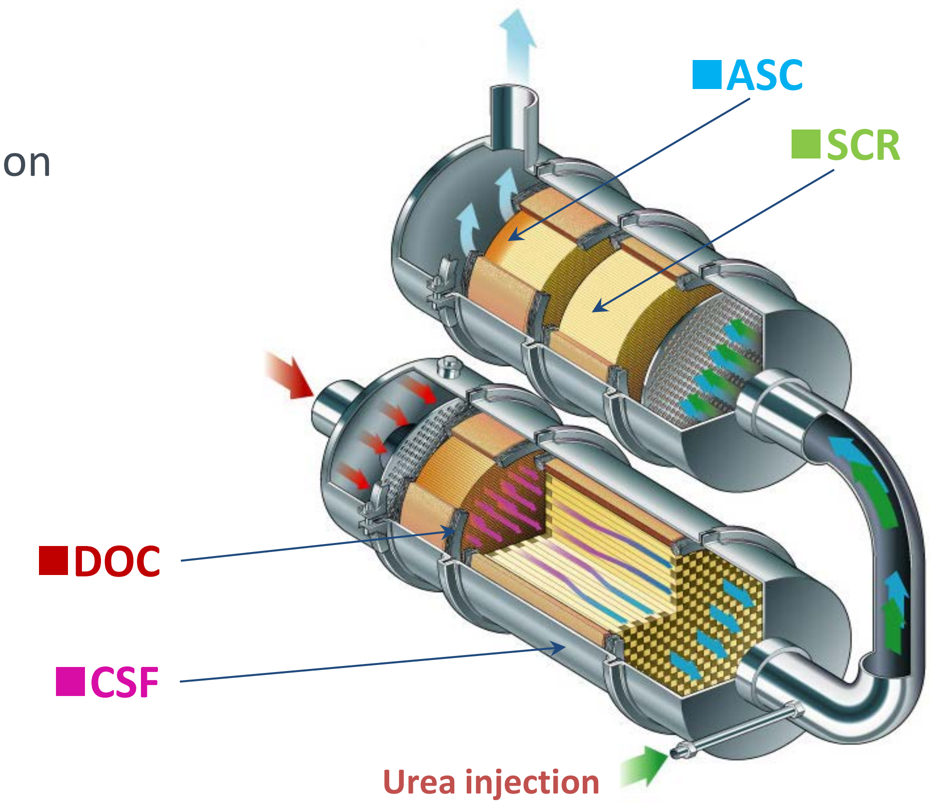
- Traps particulate matter (carbon)
  - For subsequent removal by NO_2 and / or O_2
- Enables particle number (PN) compliance

SCR – Selective Catalytic Reduction

- Removes NO_x via reaction with NH_3

ASC – Ammonia Slip Catalyst

- Removes any ammonia (NH_3) slip and converts it to (predominantly) nitrogen (N_2)



EPA 10/Euro VI Systems: DOC + CSF + SCR + ASC

JM Offers Variety of SCR Technologies to Meet High NOx Reduction

For systems with CSF (active regeneration systems), thermally durable SCR is required

- Zeolite-based SCR systems will be used; Also developing new V based one
- JM offers Cu or Fe zeolite catalysts
  - Cu SCR requires high temperature treatment for de-sulfation (ie higher fuel, higher PGM DOC)
  - Fe requires NO_2 and management of coke/HC level (ie high PGM DOC)

SCR	NO2 Need	Sulfur sensitivity	HC Coking	Thermal Resistance	DOC/CSF PGM Loading
Cu	Low	High	Low	Very high	Med
Fe	High	Low	High	High	High
V	Med	Low	Low	Low	Low

Current System Designs in the Non Road Market

Non-road

- Aligned standards in Europe, North America and Japan
- **80%** reduction in NO_x limit for Tier 4b (2014)
  - Optimised **SCR systems** required
- No particle number limit
- Filters **not required** to meet the non-road Tier 4b regulations
- **SCR** is required; typical systems:
  - SCR + ASC
  - DOC + SCR + ASC
  - DOC + CSF + SCR + ASC

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On Road (EUVI, EPA10) vs Non Road (T4B) Regulations

T4B has higher limits and no need for DPF on all engines

	EU VI	EPA10	Tier 4B
NO_x (mg/kWh)	**400**	**270**	**400**
PM (mg/kWh)	**10**	**13**	**25**
PN (#/kWh)	**6×10^{11} (WHTC)** **8×10^{11} (WHSC)**	**No limit**	**No limit**
Cycles	ESC & ETC (WHSC & WHTC)	FTP & SET	NRTC & NRSC
OBD	Yes	Yes	In preparation
Introduction	12/31/13	1/1/10	1/1/14 (130-560kW) 1/1/15 (56-130kW)

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So What Will Change Going Forward?

- Further fuel economy improvements
  - Increases in engine-out NO_x (and NO_x/PM ratios)
  - Reductions in exhaust temperature
  - Reductions in system backpressure

- Further regulatory reductions in NO_x emissions
  - **Increases in system NO_x conversion requirements**

- Further implementation of DPFs (PN compliance)
  - eg non road Stage V in Europe

- Increased focus on other emissions
  - N_2O, NO_2, CH_4, Black Carbon etc.

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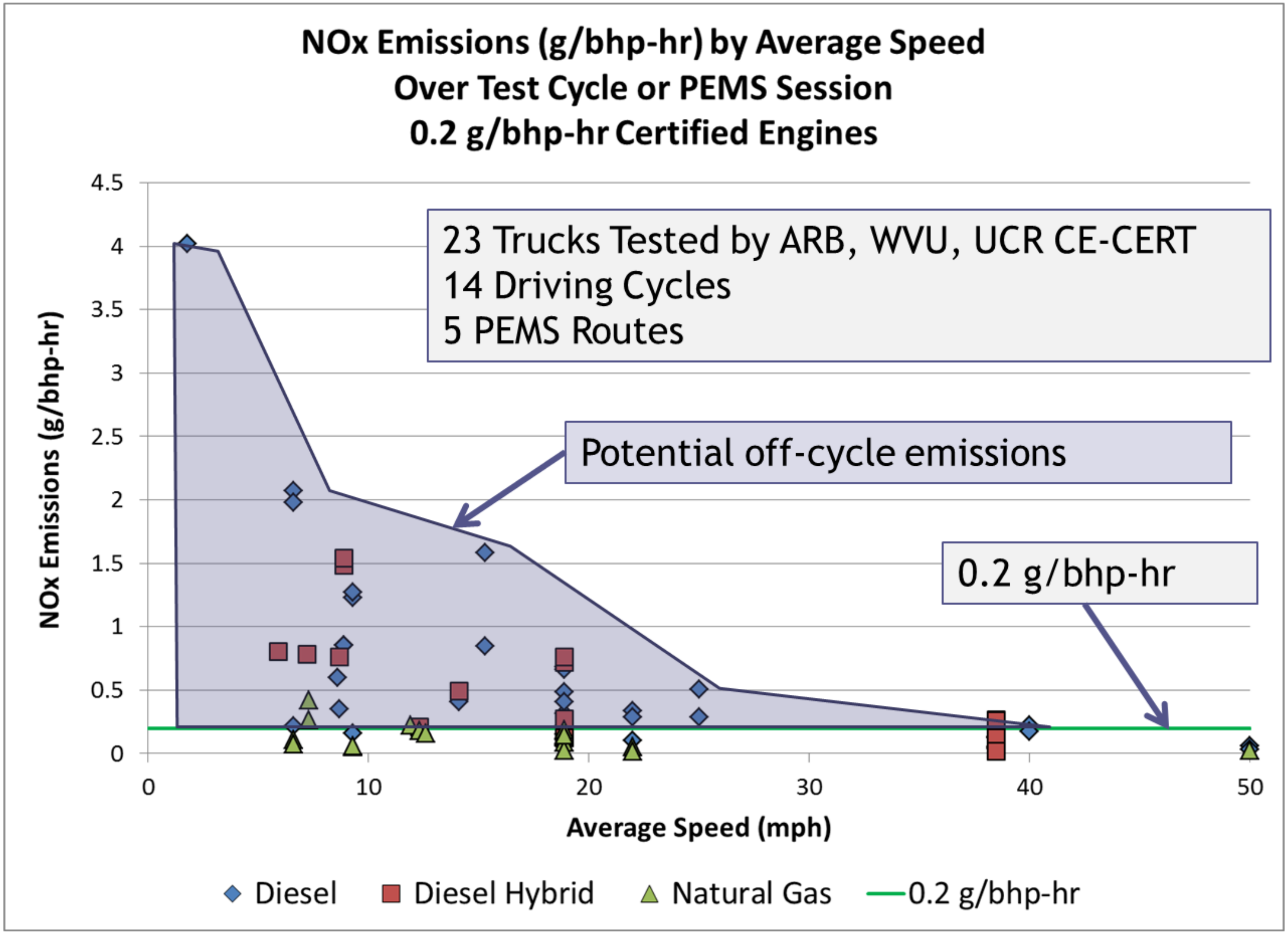
Strengthening the Current Standard: Off-Cycle NOx Emissions Are a Concern

Source: CARB (Erik White) SAE HDD Symposium Presentation: September 2014



Future ARB Regulations

- Proposed Optional Standards
  - 0.10 g/hp-hr
  - 0.05 g/hp-hr
  - 0.02 g/hp-hr

- GHG neutral, so very high NO_x conversion required
  - For 3g NO_x engine, **98.4% cold FTP + 99.5% hot FTP**
  - Strong focus expected on cold start NO_x control:
    - ➢ New cold start NO_x control technologies needed

- Possible approaches:
  - How far can Natural Gas-based approaches take us?
    - ➢ Can they get to 0.02 g/hp-hr?
    - ➢ Could NG-hybrids hit 0.01 g/hp-hr?

- 25% of engine families certified to below 0.2 g/hp-hr in 2007-12
  - 0.03 – 0.14 g/hp-hr

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Incoming Technologies: Extruded/High Porosity Substrate with Increased Cell Density

- The SCR reaction is kinetically controlled at low temperatures
  - Increasing the number of active sites will promote low temperature activity
- The SCR washcoat loading can be effectively increased by using an extruded catalyst or by using a high washcoat loading on a High Porosity Substrate (HPS)
  - Enabling enhanced low temperature performance with minimal backpressure increase
- Increasing the cell density from e.g. 400 to 600 cpsi leads to improved high temperature performance
  - The SCR reaction is mass transfer limited at high temperatures

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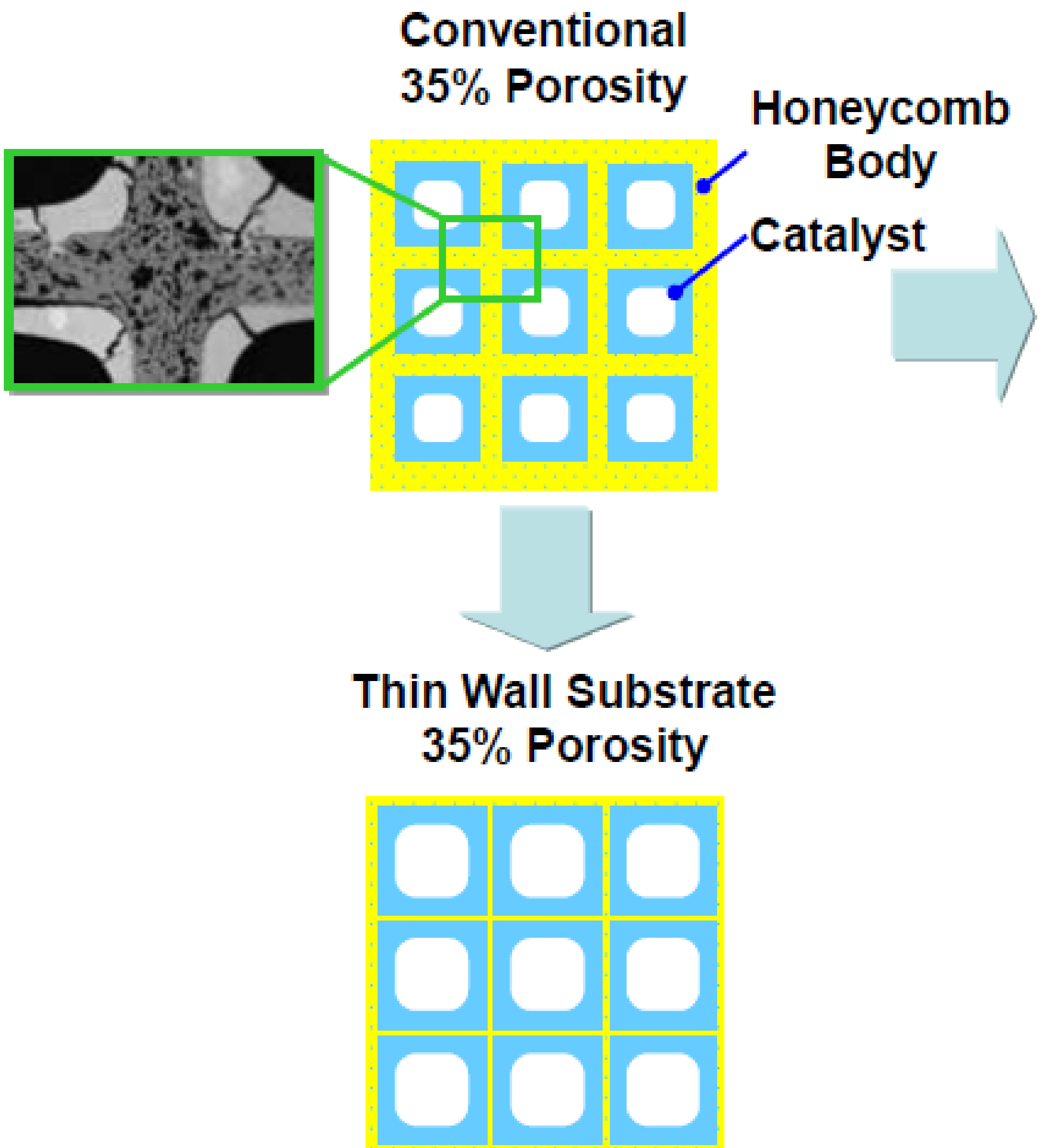
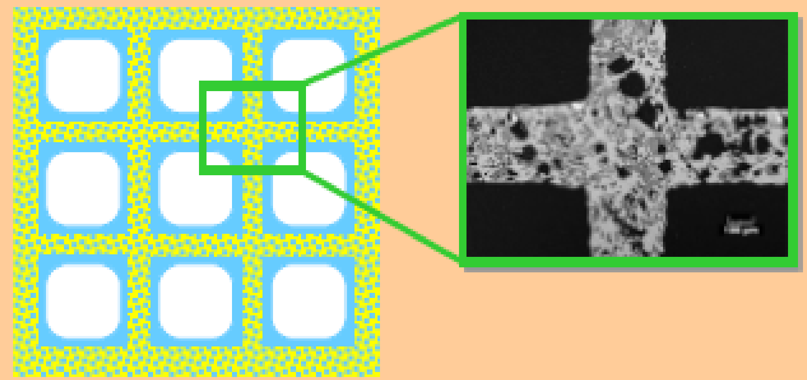
High Porosity (HP) Substrate Material



High Porosity (HP)
50% (~65%) Porosity



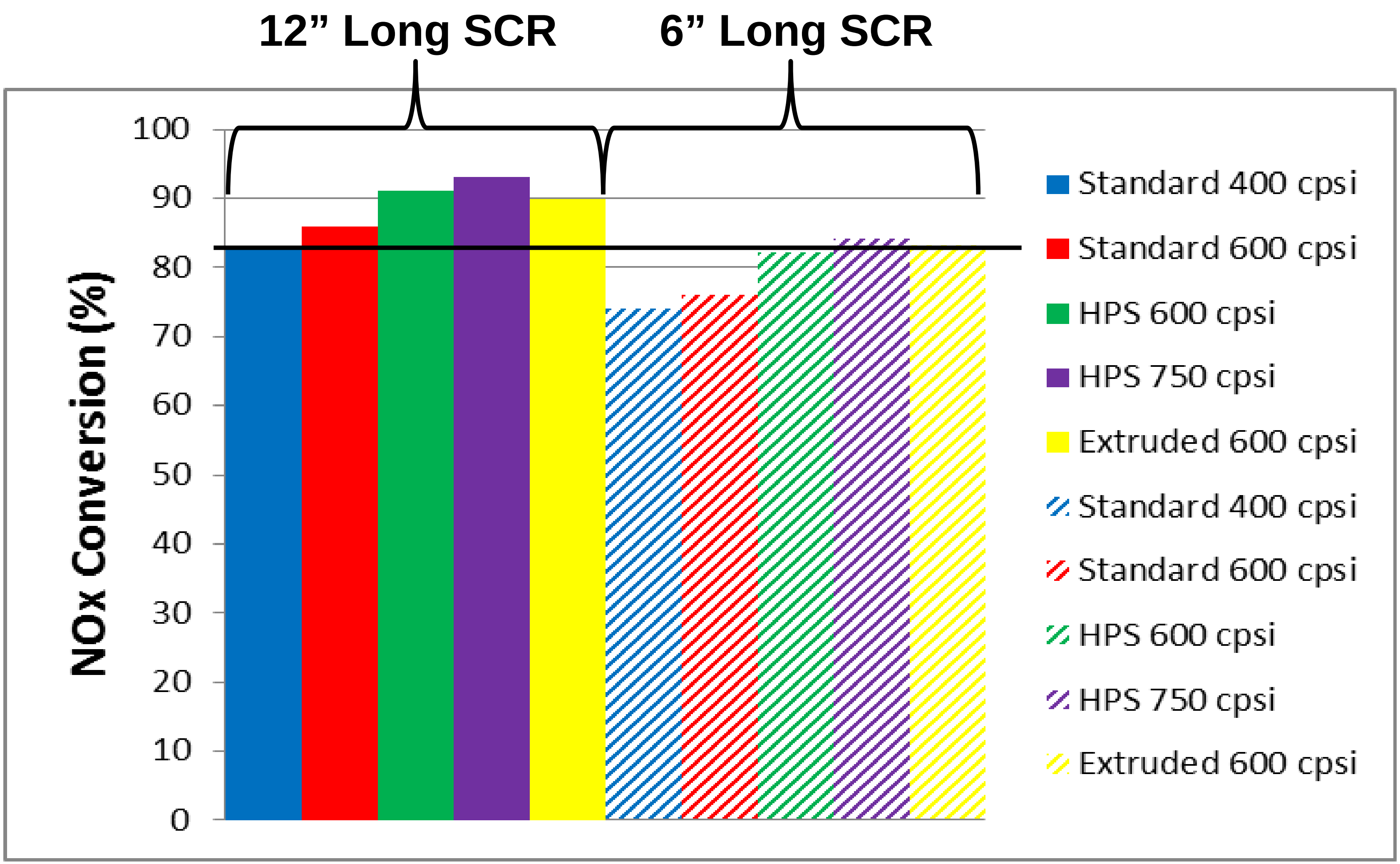
Catalyst coating into pores of the honeycomb-body

- **Lower pressure drop with the same catalyst loading**
- **Higher catalyst loading under the same pressure drop**

(Higher NOx conversion)

Comparison of CuSCR on Various Substrates

HPS and Extruded potentially enable up to 50% volume reduction



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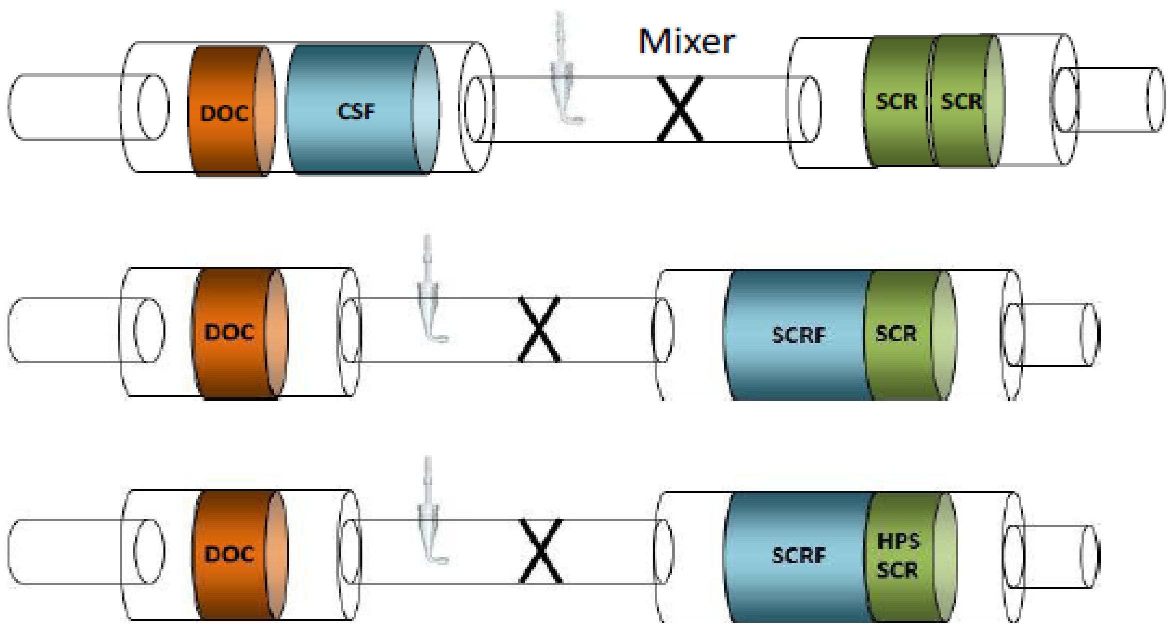
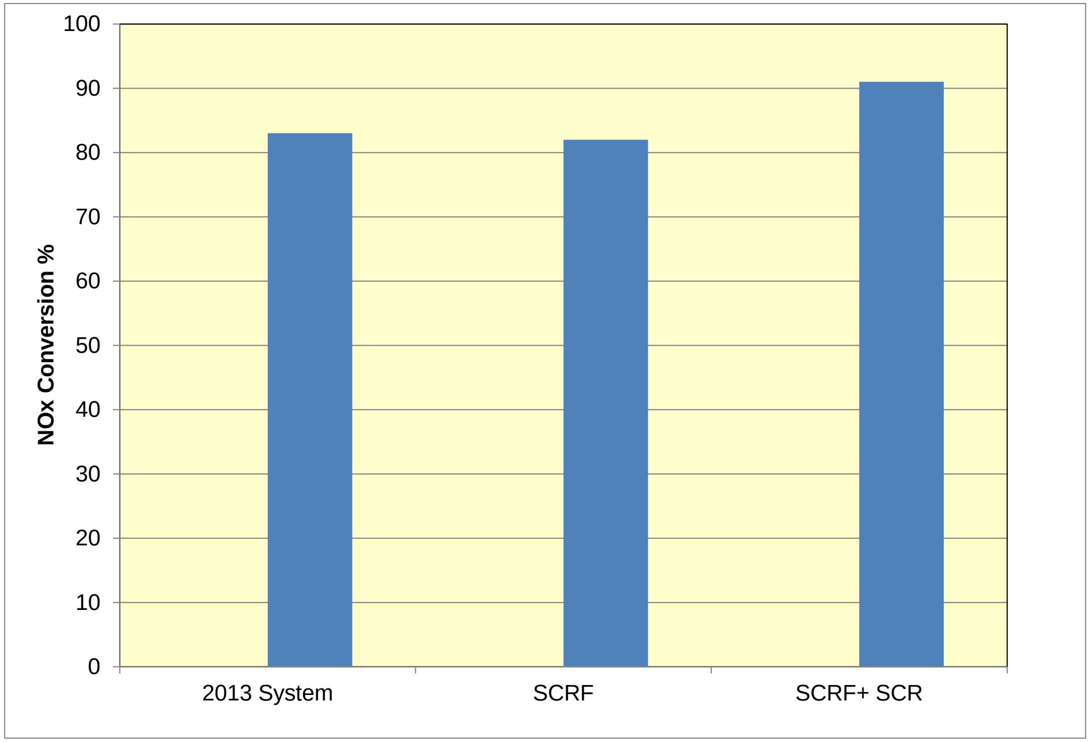
Incoming Technologies: SCRF® Component

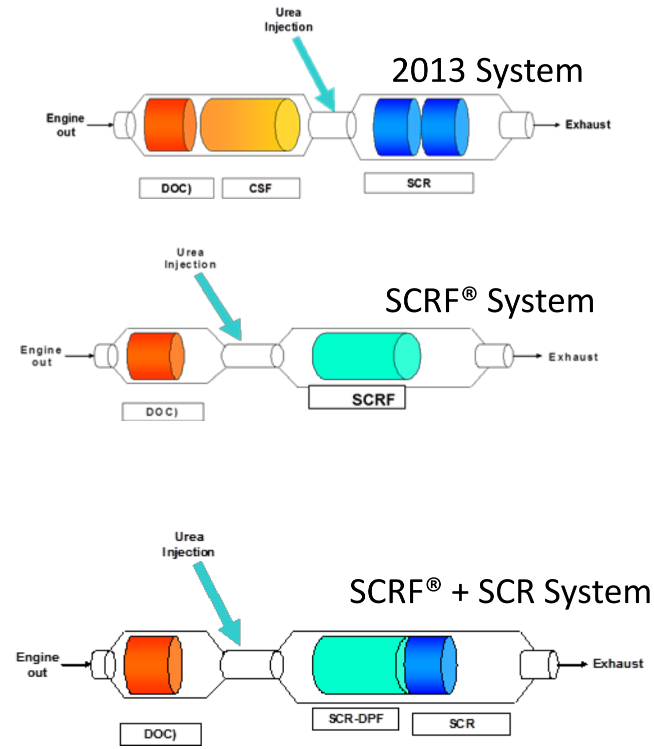
- Applying an SCR coating to the filter enables:
  - SCR component to get hotter earlier – increased NO_x conversion
  - Increased SCR volume in the system – increased NO_x conversion
  - Increased PN filtration efficiency
  - Increased competition for NO_2 between PM combustion and NO_x conversion
    - potential reduction in passive filter regeneration



SCRF Provides Significant Performance Advantages

Optimized Formulation Can Provide Significant Volume Reduction



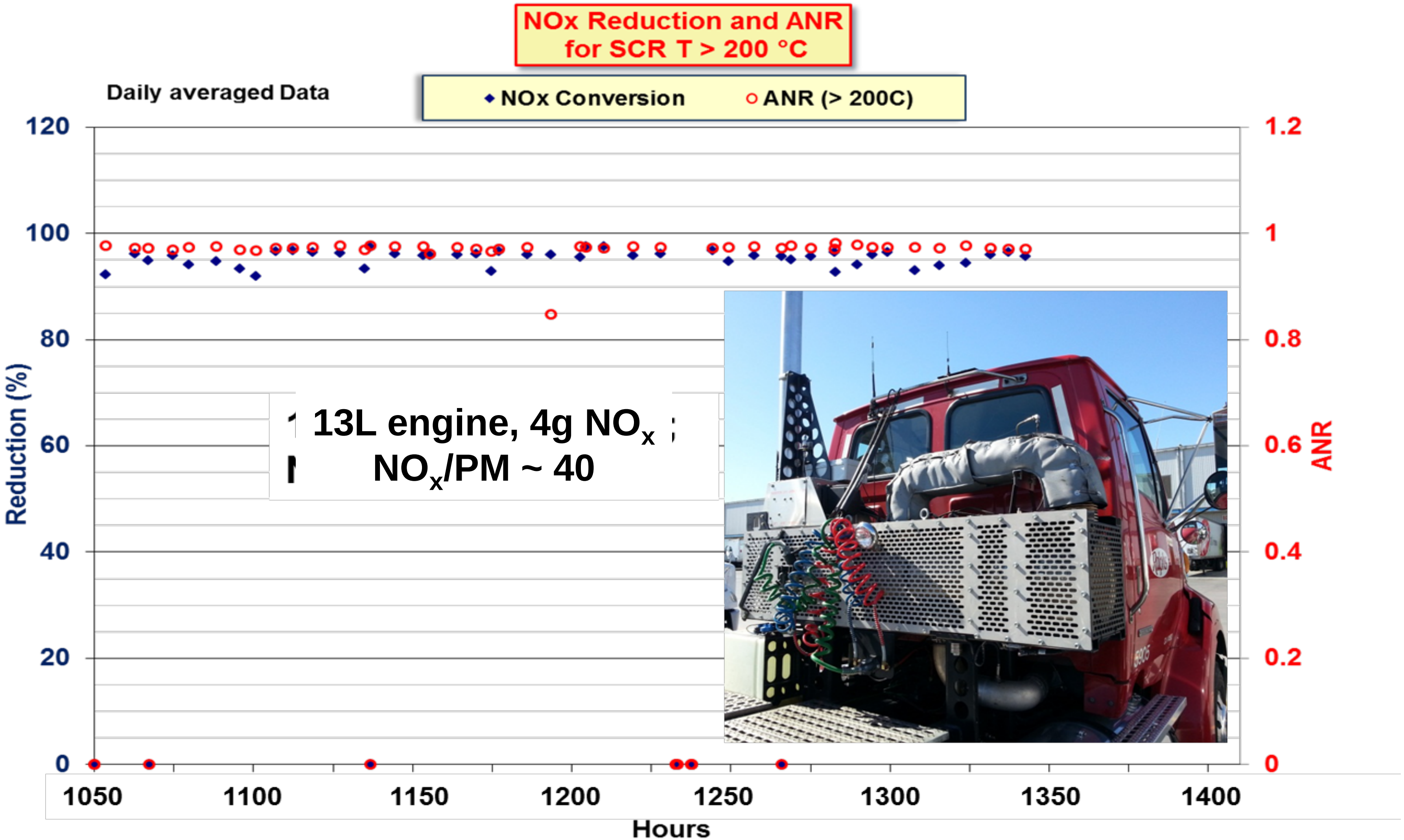


AT Volume optimization strategy	2013	SCRF® Only	SCRF®+SCR
volume reduction of catalyst	base	~ 38%	~ 20%

- Ability to meet more stringent deNO$_x$ requirements
- Potential for significant system volume reduction
- Allow high engine-out NO$_x$
  - Promote passive regen (high NO$_x$ /PM)
  - Improve fuel efficiency and GHG control

Very High Average Daily NO_x Conversion After 1 Year in Operation

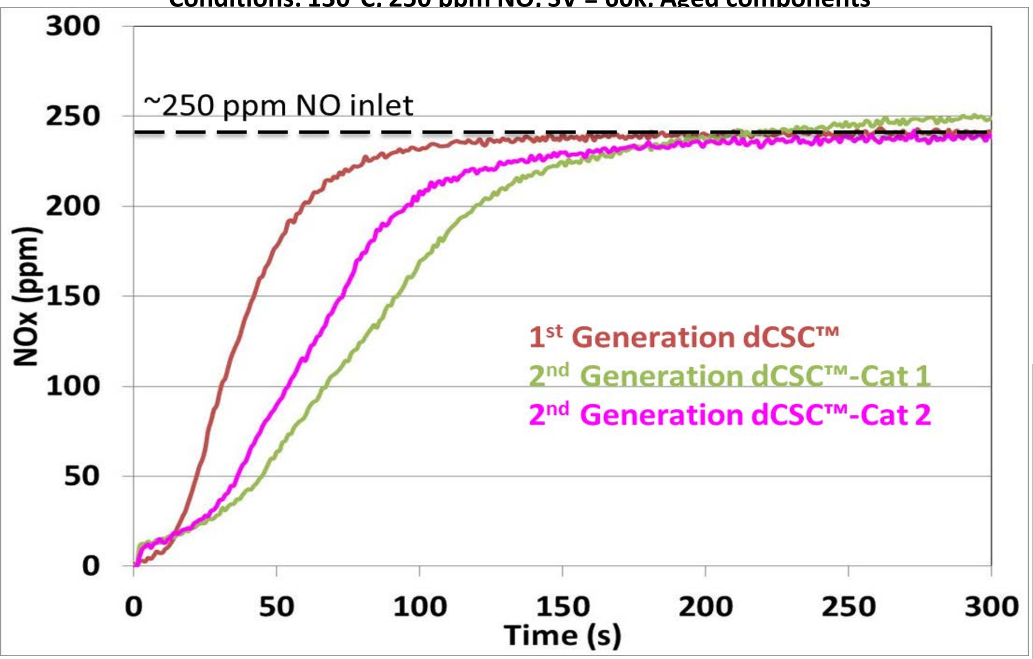
DOC + SCRF + SCR + ASC



Incoming Technologies: dCSC (Diesel Cold Start Catalyst) Component

NOx Storage:

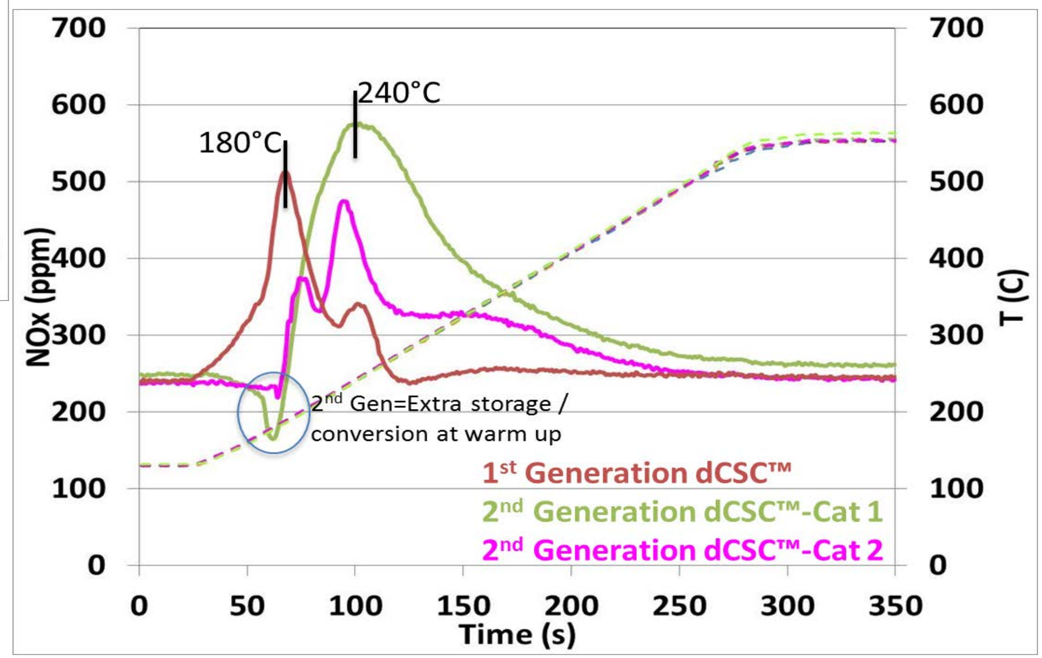
Conditions: 130°C, 250 ppm NO, SV = 60k, Aged components



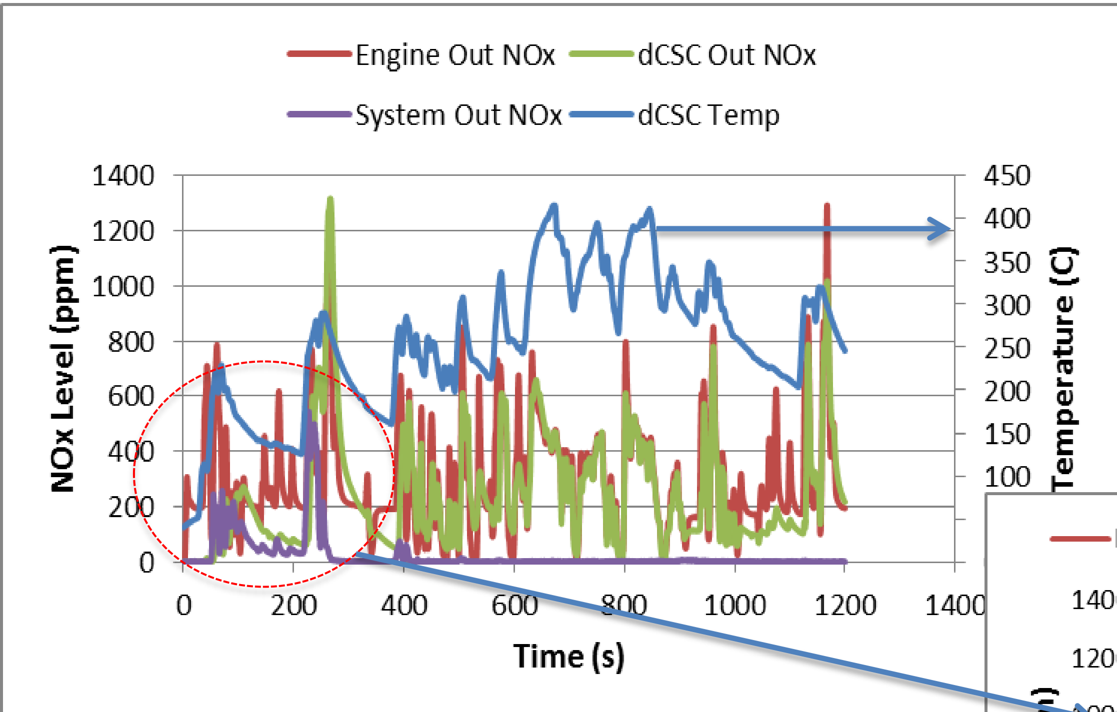
Concept: Trap NOx from cold start, and release when downstream SCRF® component is hot enough to convert the NOx; Passive System

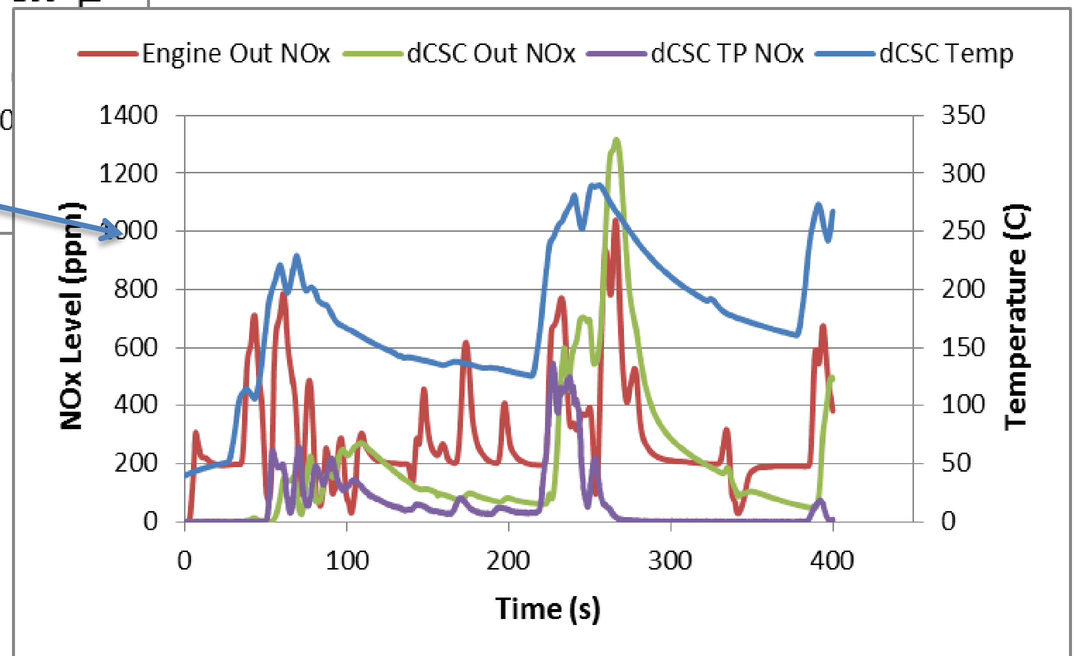
NOx Release:

Conditions: Ramp at 100°C/min, SV = 60k, Aged components



Under Low Temperature Cycle, dCSC™ + SCRF® Combination Provides Very High NOx Removal

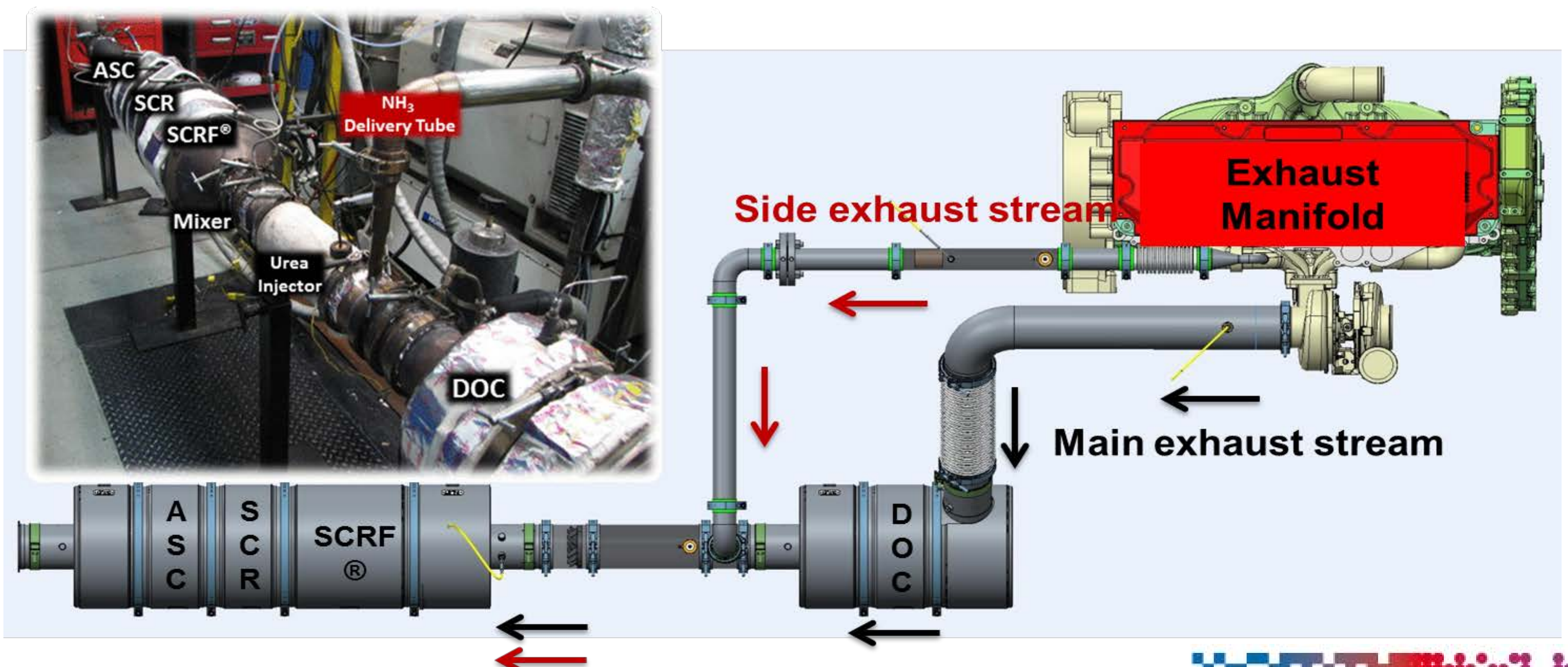




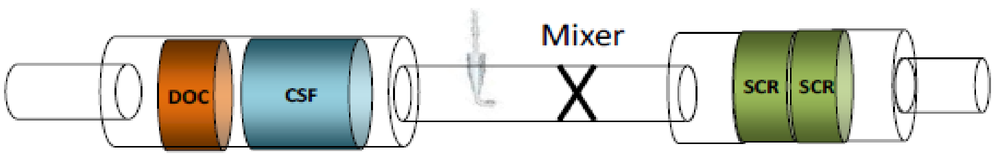
During the very low temperature of first 200 Seconds of Cold FTP cycle, dCSC stores NOx and releases when the SCRF is warm to provide high NOx conversion

Incoming Technologies: Low Temperature Ammonia Availability

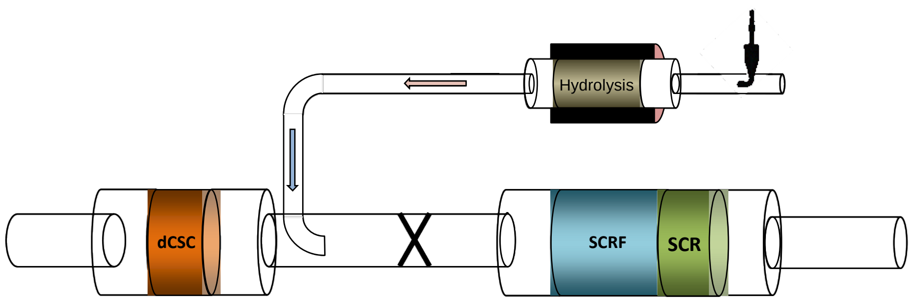
- Under Cold temperature conditions, limitation in Urea dosing limits NH_3 availability
- Auxiliary side reactor based NH_3 dosing system can be designed to deliver NH_3 at low temperature
- Side system pulls hot exhaust from pre-turbo
- Urea is injected into side system, hydrolysis catalyst converts urea to NH_3
- Gaseous NH_3 is delivered to SCRF component inlet at low temperature
- Side NH_3 doser and main urea injection used in tandem during transient cycle



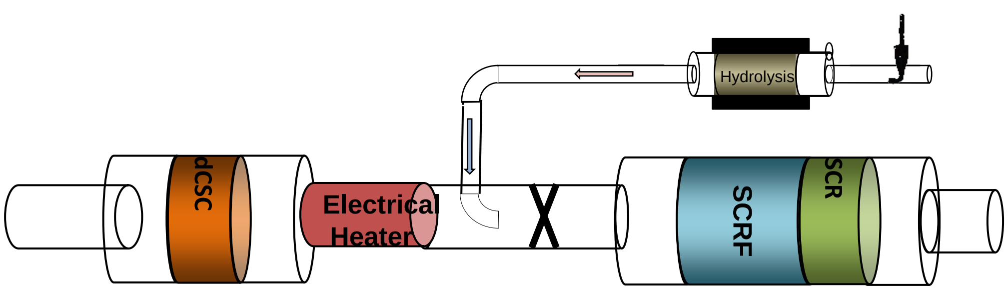
Innovative System Configurations will Allow for Very High NO_x Removal



Reference System
DOC + CSF + SCR + SCR

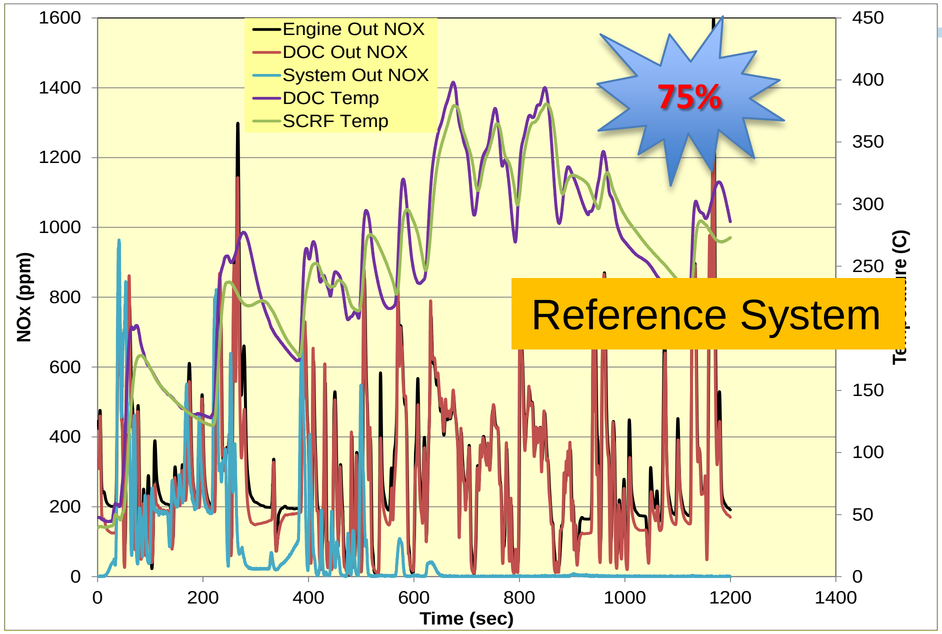


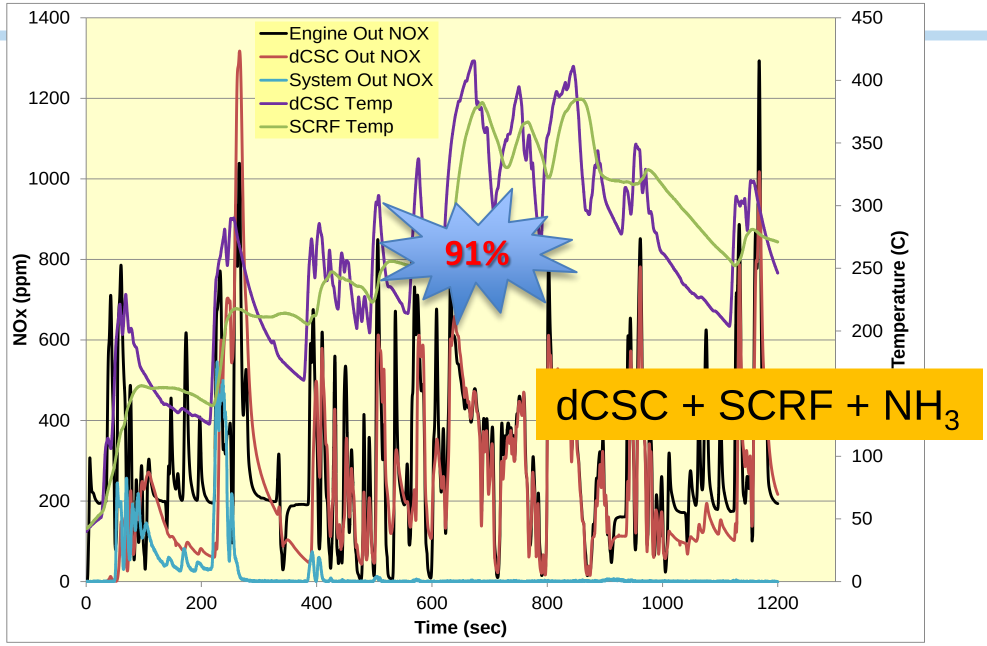
Future System – 1: Early NH_3
dCSC + SCRF + SCR

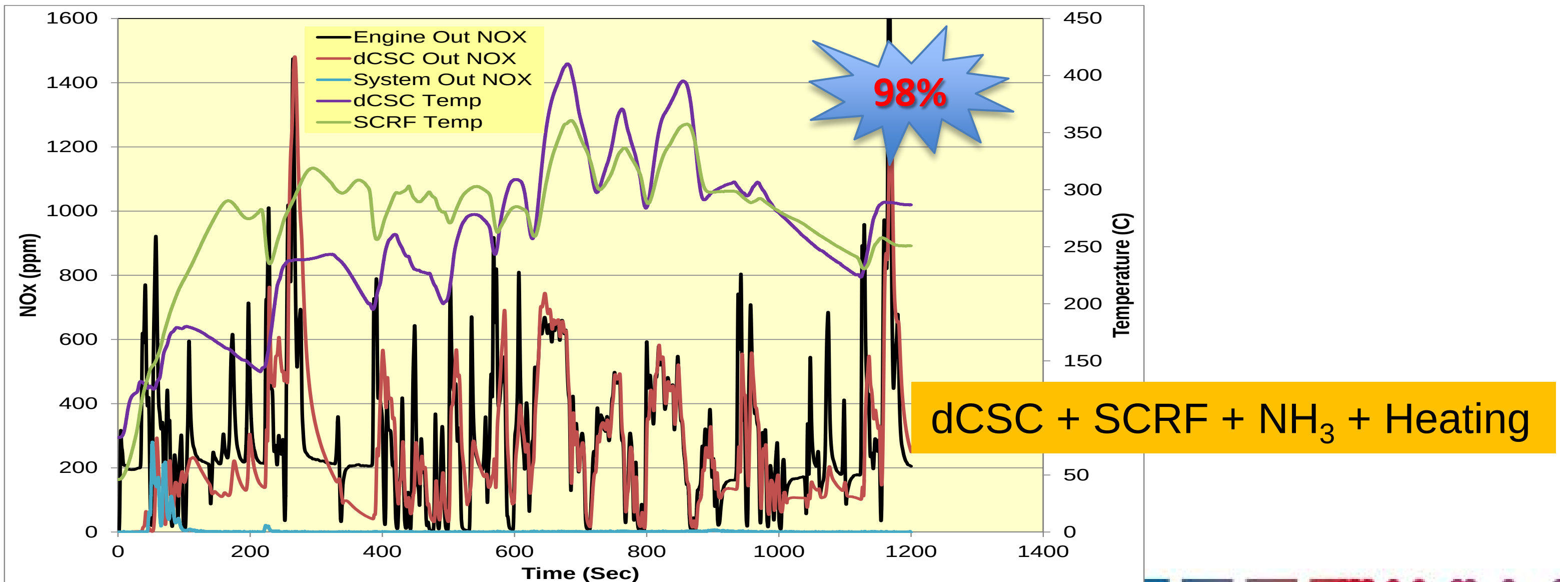


Future System – 2: Early NH_3 + Heating
dCSC + SCRF + SCR

Innovative System Configurations Will Allow for Very High NO_x Removal







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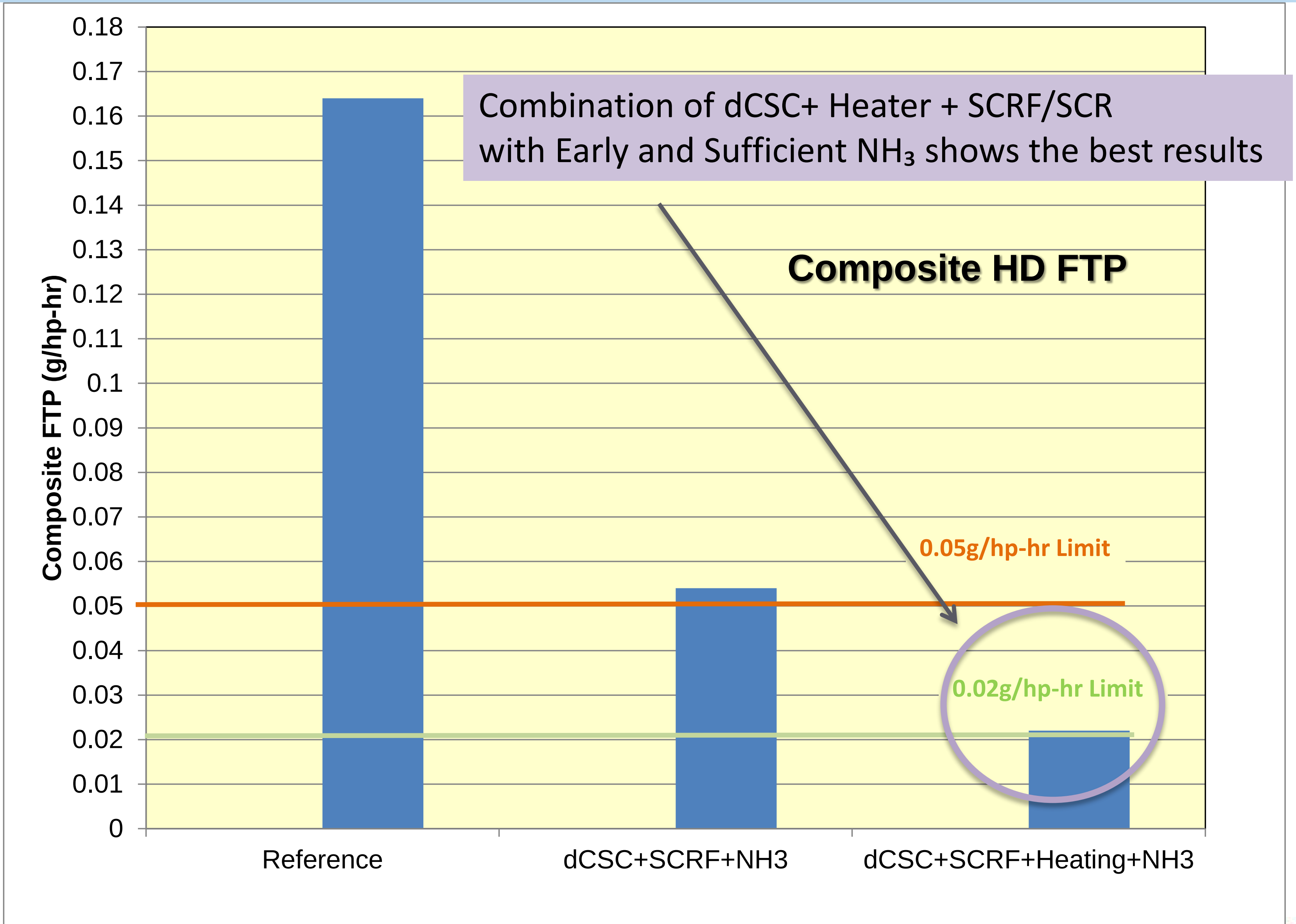

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- PM control using DOC/DPF and NO_x ($NO + NO_2$) control using SCR is established methods for Diesel Engine emission control
- SCR is highly efficient and cost effective way of catalytic reduction of NO_x; It is the primary method utilized in Euro IV/V/VI and future systems
- Highly active V-based SCR catalysts have been developed and well proven for Euro IV/V applications
- Advanced regulations such as US 10/Euro VI require more advanced integrated systems and use zeolite based SCR catalysts along as well as V SCR
- Further improved SCR catalysts are being developed to meet proposed future regulations for ultra low NOx emissions, emphasising on cold start conditions
- Besides tradition SCR catalyst, multifunctional SCRF and dCSC systems have been developed to achieve very high NO_x conversions & improved fuel economy
- Low temperature NO_x conversion can be increased by a range of strategies such as early NH_3 dosing, thermal management, etc., in combination with advanced multifunctional system

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