APBF-DEC Heavy-Duty NO_x Adsorber/DPF Project: Catalyst Aging Study

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August 30, 2004

Presented at: 10th Annual Diesel Engine Emission Reduction Conference
San Diego, California

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Advanced Petroleum Based Fuels – Diesel Emission Control Study

Government/Industry Sponsorship

Systems Projects

NO_x Adsorber/DPF			SCR/DPF	Lubes
				
FEV	SwRI	Ricardo	SwRI	AEI
1.9L TDI	6.6L Isuzu Duramax	15L Cummins ISX	Caterpillar C12	Cummins ISB
Audi A4 Avant	Chevrolet Silverado	*No vehicle*		

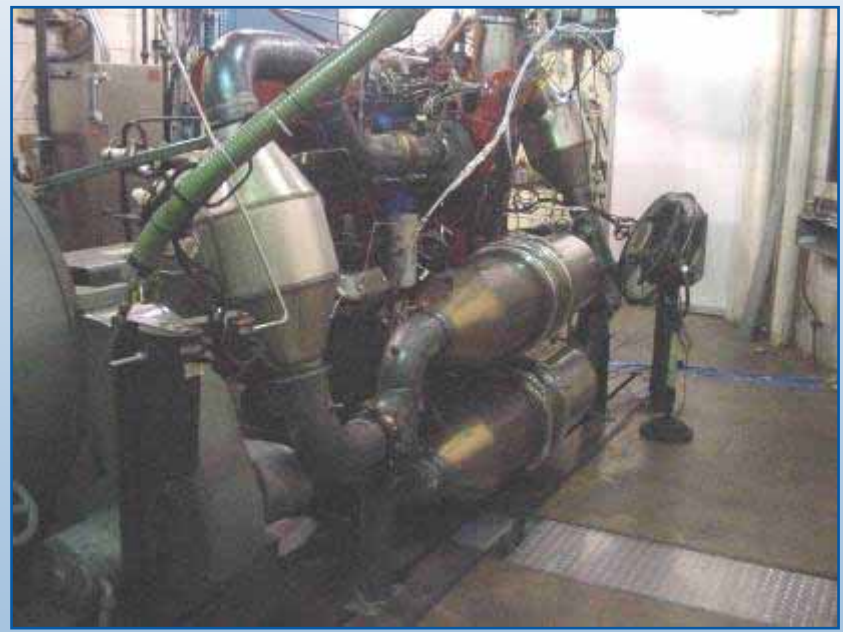
HD NOx Adsorber/DPF Project

Project Scope

- Develop system capable of meeting 2010 emissions standards:
  - 0.20 g/bhp.h NOx and 0.01 g/bhp.h PM
- Develop sulfur management strategy
- Conduct 2000 hour catalyst aging test
  - Transient and steady-state evaluations of:
    - Regulated emissions
    - Currently unregulated emissions

Test Laboratory

- Project conducted at Ricardo's Chicago Technical Center (Burr Ridge, IL)
- Project staff:
  - Mike May
  - Brad Adelman
  - Joe McManus
  - James Baustian
  - Graham Weller
  - Florin Tamas

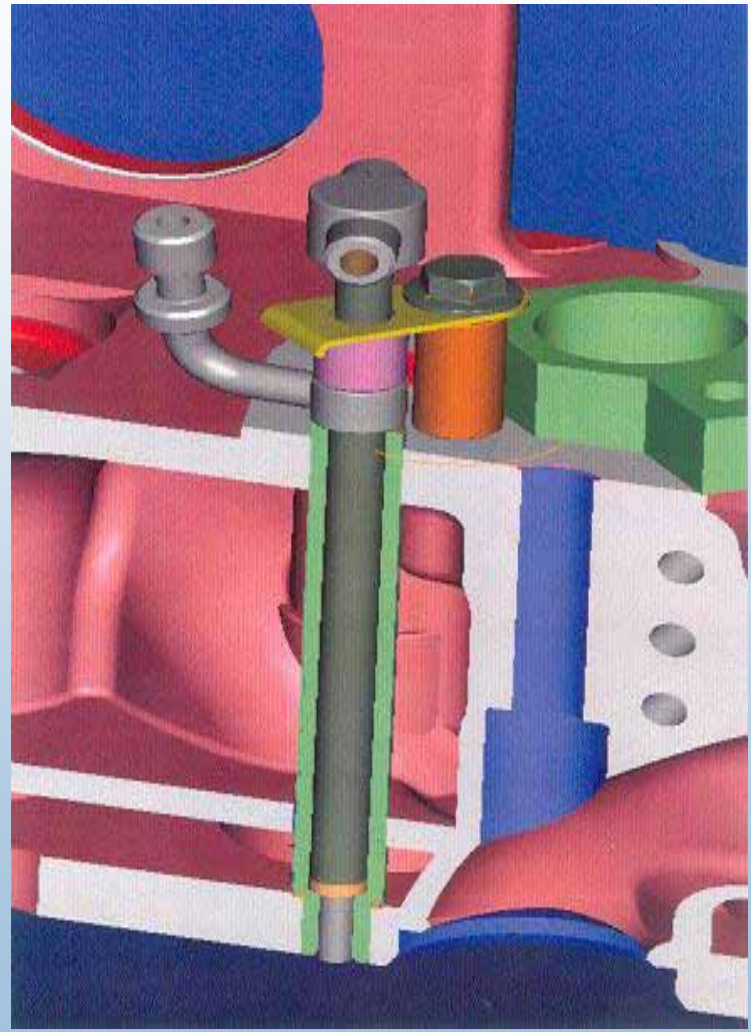


Test Engine

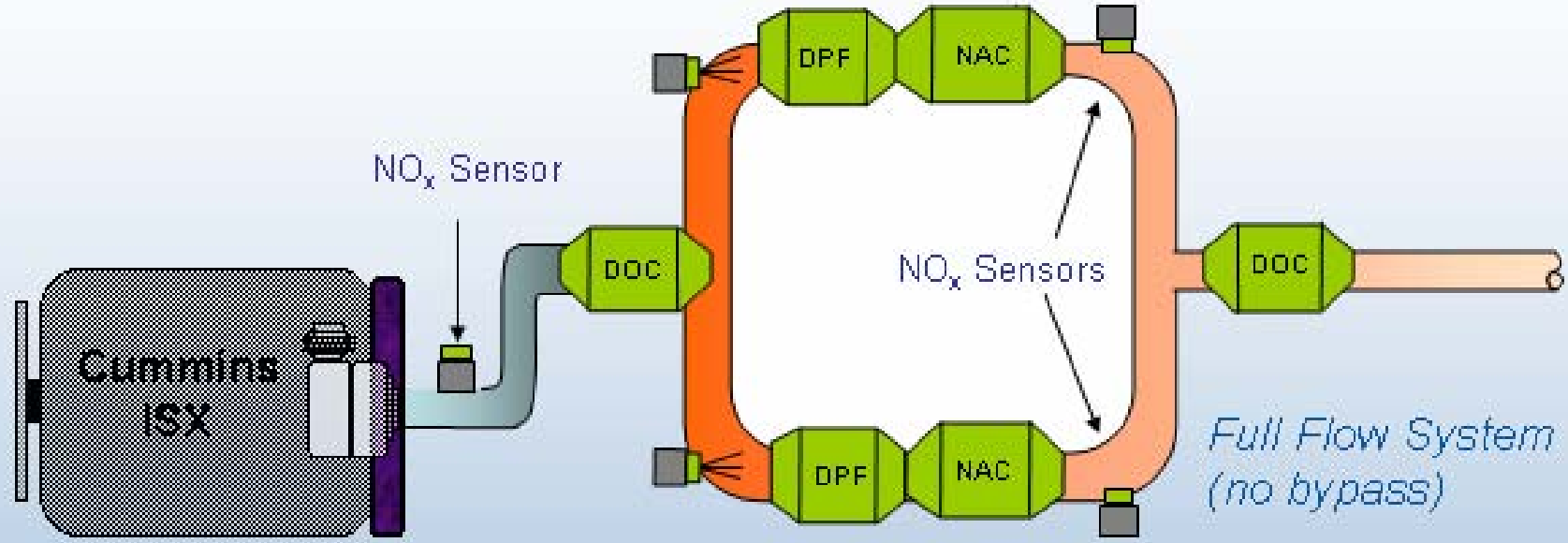
- Cummins ISX 15L
- 475 hp Rating
- DOHC 4V central EUI
- Cooled EGR, VGT
- Advanced electronic controls
- 2002/2004 Base engine out emissions (pre-production)

Engine Modifications

- In-cylinder post injection system with separate injector and pump
- In-exhaust fuel injectors
- Intake throttle
- Auxiliary control system to handle rich engine operation
- Boost by-pass for DOC



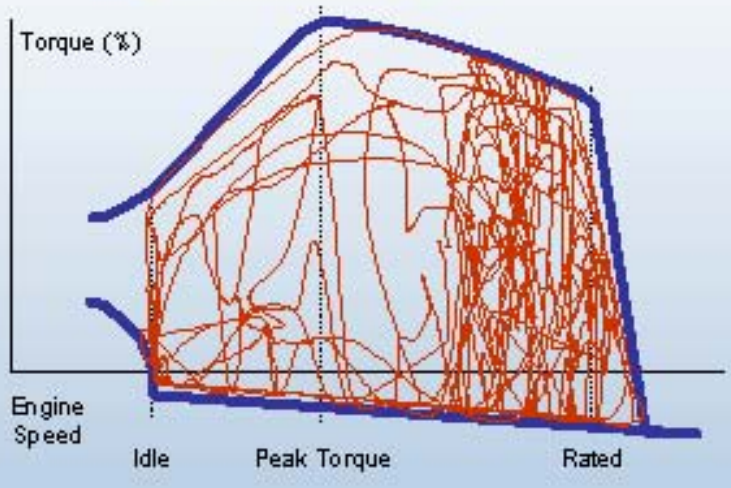
Emission Control System



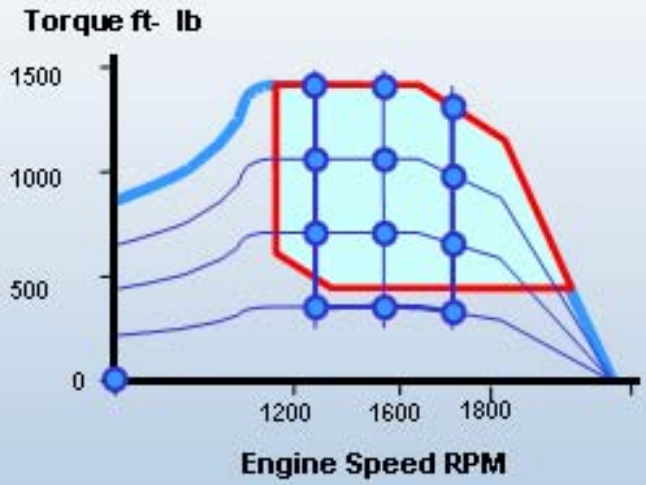
Device	**Dimensions** (Diameter x Length)	**Volume**
Upstream DOC	12” x 6”	11.1 L
DPF (x2)	12” x 14”	25.9 L (51.8 L total)
NO_x Adsorber Catalyst (x2)	12” x 12”	22.2 L (44.4 L total)
Clean-up DOC	12” x 6”	11.1 L
	Total Volume:	118 L

Test Cycles

HD Transient FTP



Supplemental Emission Test (SET)



1 Cold FTP

Multiple Hot Cycles (3 or 6)

Emission Measurements

- Dilute emissions including:
  - NOx, Total HC, NMHC, CO, CO2, N20
- Raw emissions, engine out and tailpipe:
  - NOx, Total HC, CO, CO2, O2
- Unregulated emissions:
  - On-line mass spectrometer analysis:
    - Benzene, 1,3-butadiene, formaldehyde, acetaldehyde, ammonia, sulfur dioxide and hydrogen sulfide
  - Bulk sampling for PAH, n-PAH, metals, nitro-organics

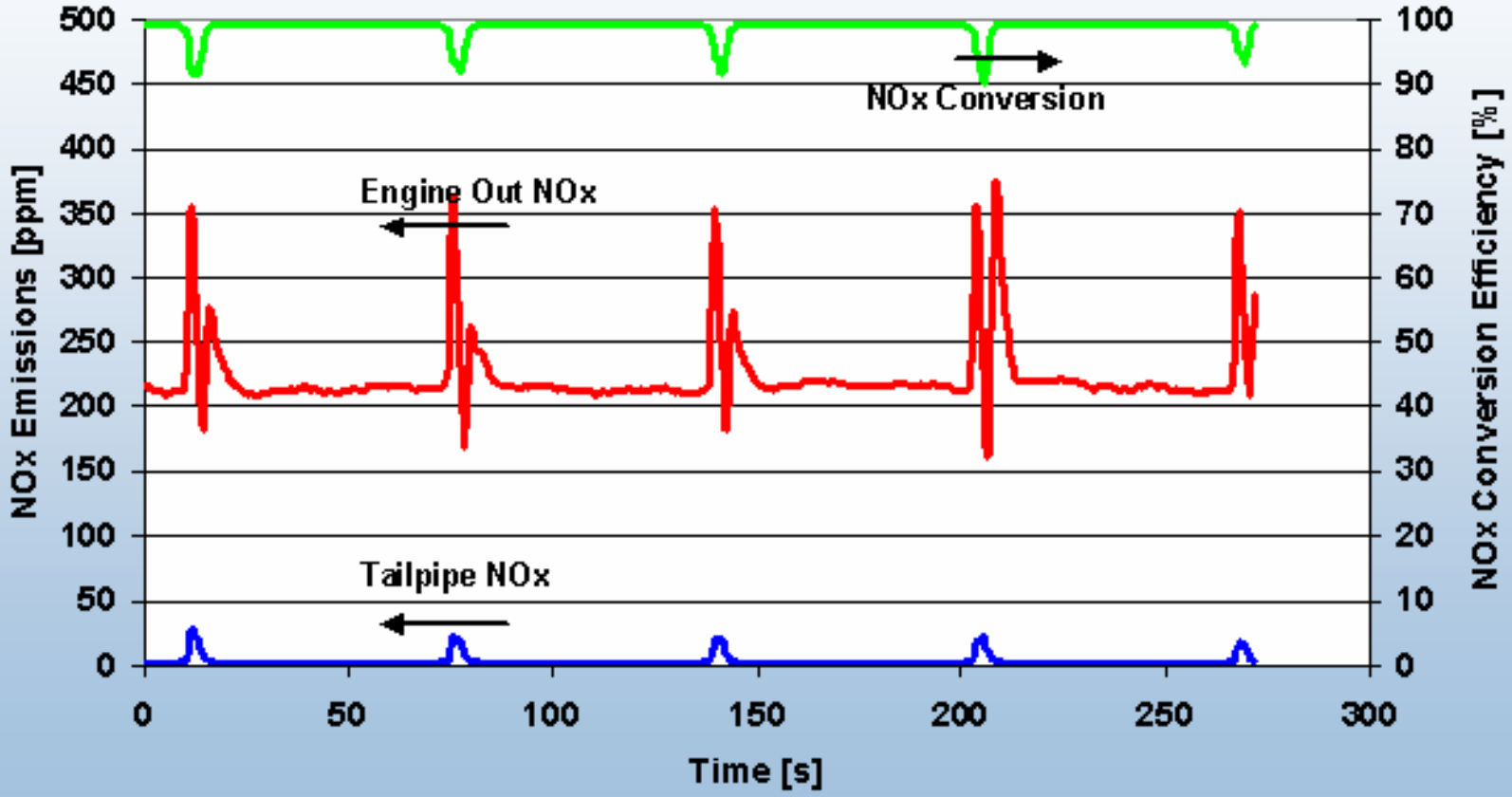
NOx Adsorber Regeneration Strategy

- Approach dictated by operating condition:
  - Intake throttling
  - Late cycle in-cylinder fuel injection
  - Increased EGR to achieve low air/fuel ratio ($\lambda<0.95$)
  - Advanced primary injection timing (to limit smoke)
  - In-pipe secondary injection (at high load conditions)

NOx Adsorber Regeneration

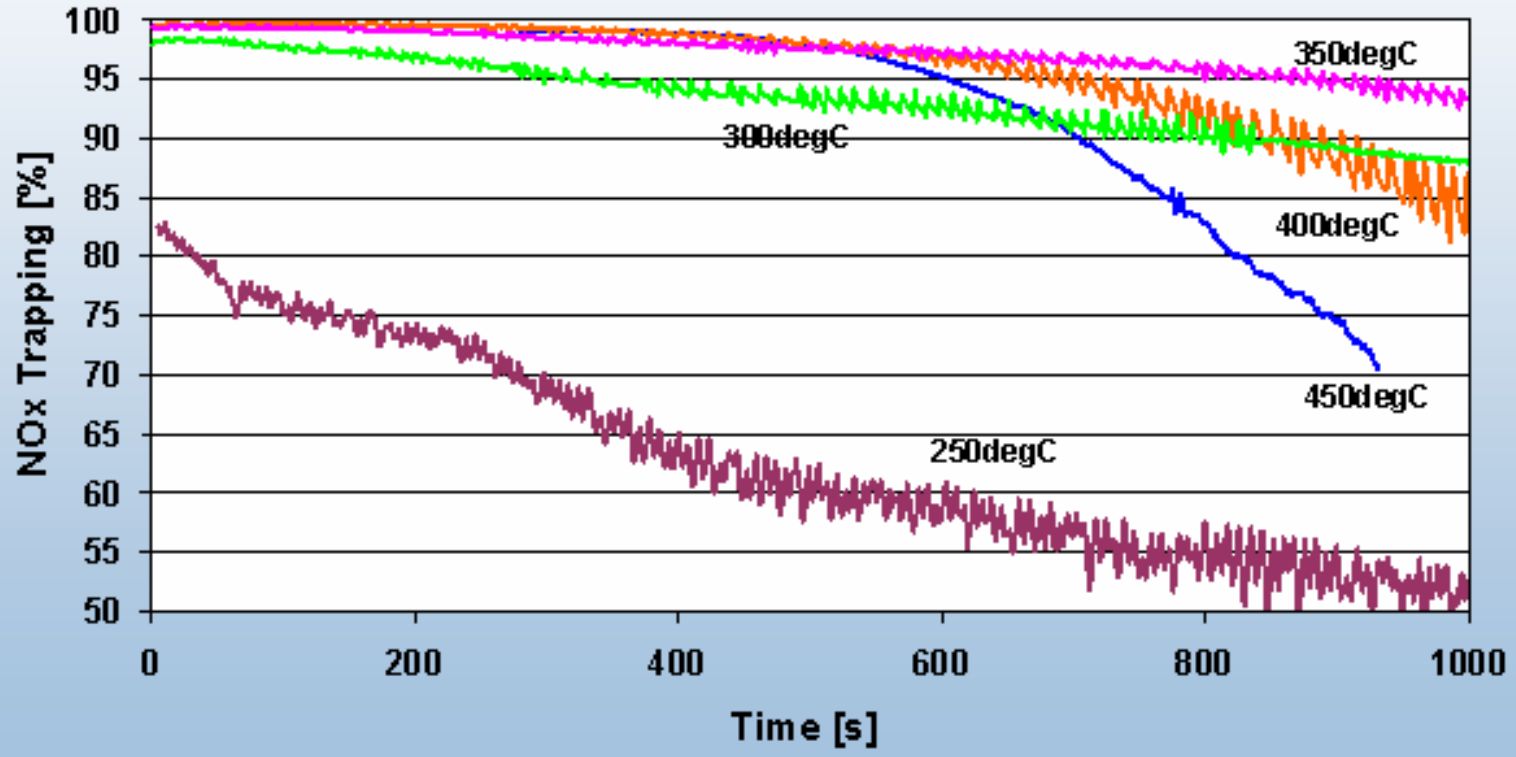
Steady-State Strategy

1800 rpm and 800 Nm – 60s/4s lean/rich (0.95-0.98 lambda)

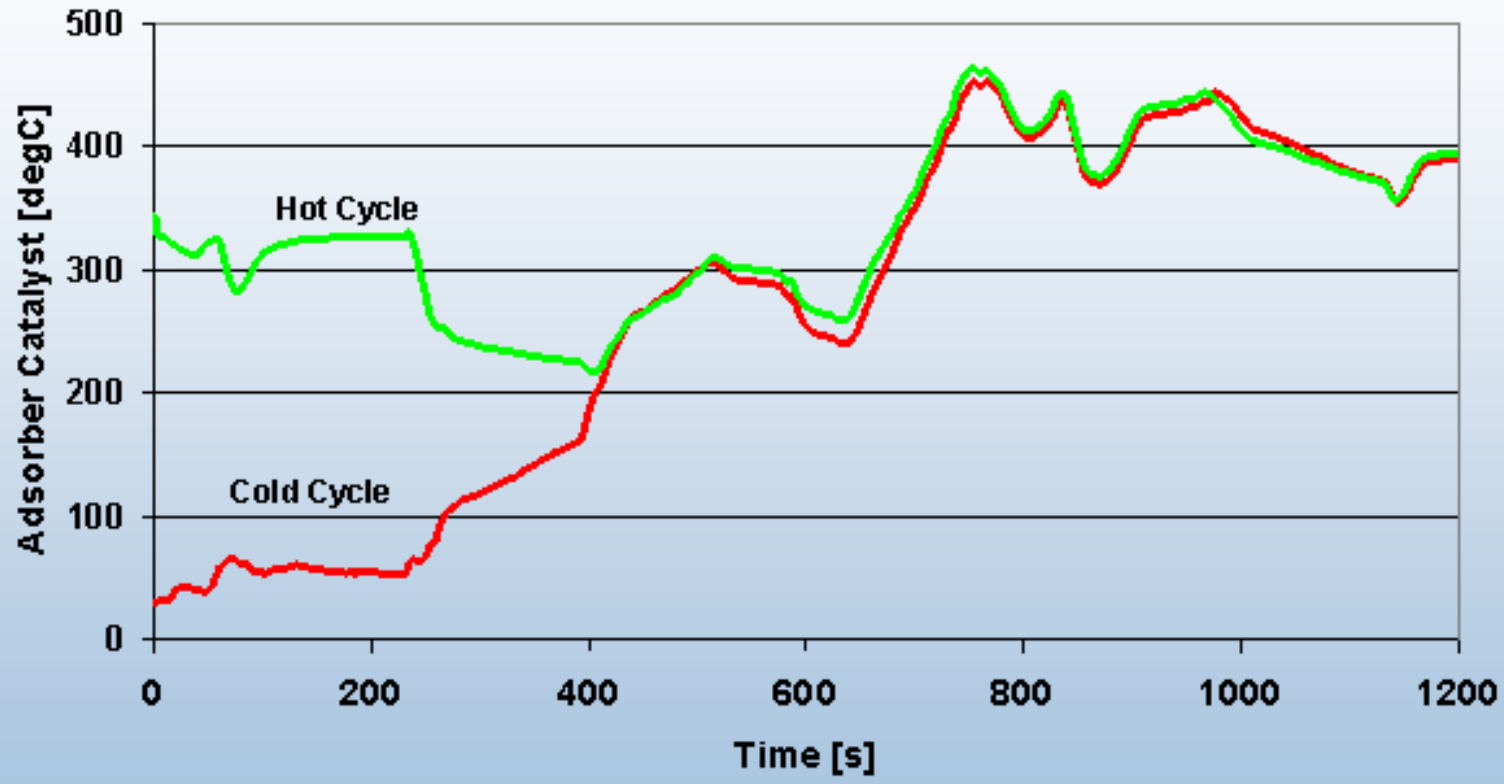


NOx Storage Capacity

- *Temperature Dependence:*



NAC Temperature Profile



Warm-up strategies including in-cylinder injection used to more rapidly increase catalyst temperature.

Summary of FTP Results
(Prior to aging study)

FTP Cycle	NO_x g/hp hr	THC g/hp hr	CO g/hp hr	Fuel g/hp hr	PM g/hp hr	Fuel S ppm
Cold	0.458	2.00	3.12	220.3	0.009	0.6
Hot	0.131	0.862	0.441	215.3	0.002	0.6
Composite	0.178	1.02	0.824	216.0	0.003	0.6
Engine-out Composite	2.30	0.297	1.12	199.6	0.133	8-15
%Reduction	92.3%	-245%	26.2%	-8.2%	97.7	

Summary of SET* Results
(Prior to aging study)

SET Test	NO_x g/hp hr	HC g/hp hr	CO g/hp hr	Fuel g/hp hr	Fuel S ppm
Tailpipe	0.141	0.056	0.039	171.0	0.6
Engine-out Composite	2.55	0.424	0.102	163.6	8-15
%Reduction	94.5%	86.9%	62%	-4.5	

* 13-mode Supplemental Emissions Test

Catalyst Desulfation

- Steady-state: 1200 rpm, 1000 Nm
- Intake throttling to lower A/F and to raise exhaust temperature.
- In-pipe fuel injection (to increase exhaust temperature)
- Targets:
  - NAC bed temperature: >650oC
  - A/F ratio: $\lambda<0.9$
- Duration: 45-60 minutes

Summary – Development Work

- NOx and PM emissions reductions of >90% have been demonstrated when appropriate operating strategies are employed
- Associated fuel economy penalty:
  - FTP: 8.2%
  - SET: 4.5%
  - Desulfation: 33%
- Challenges to certification and in-use compliance:
  - NOx adsorber catalyst regeneration at full load
  - Control of HC emission during rich regeneration.
- Results of aging studies currently being analyzed
- Final reporting is in progress

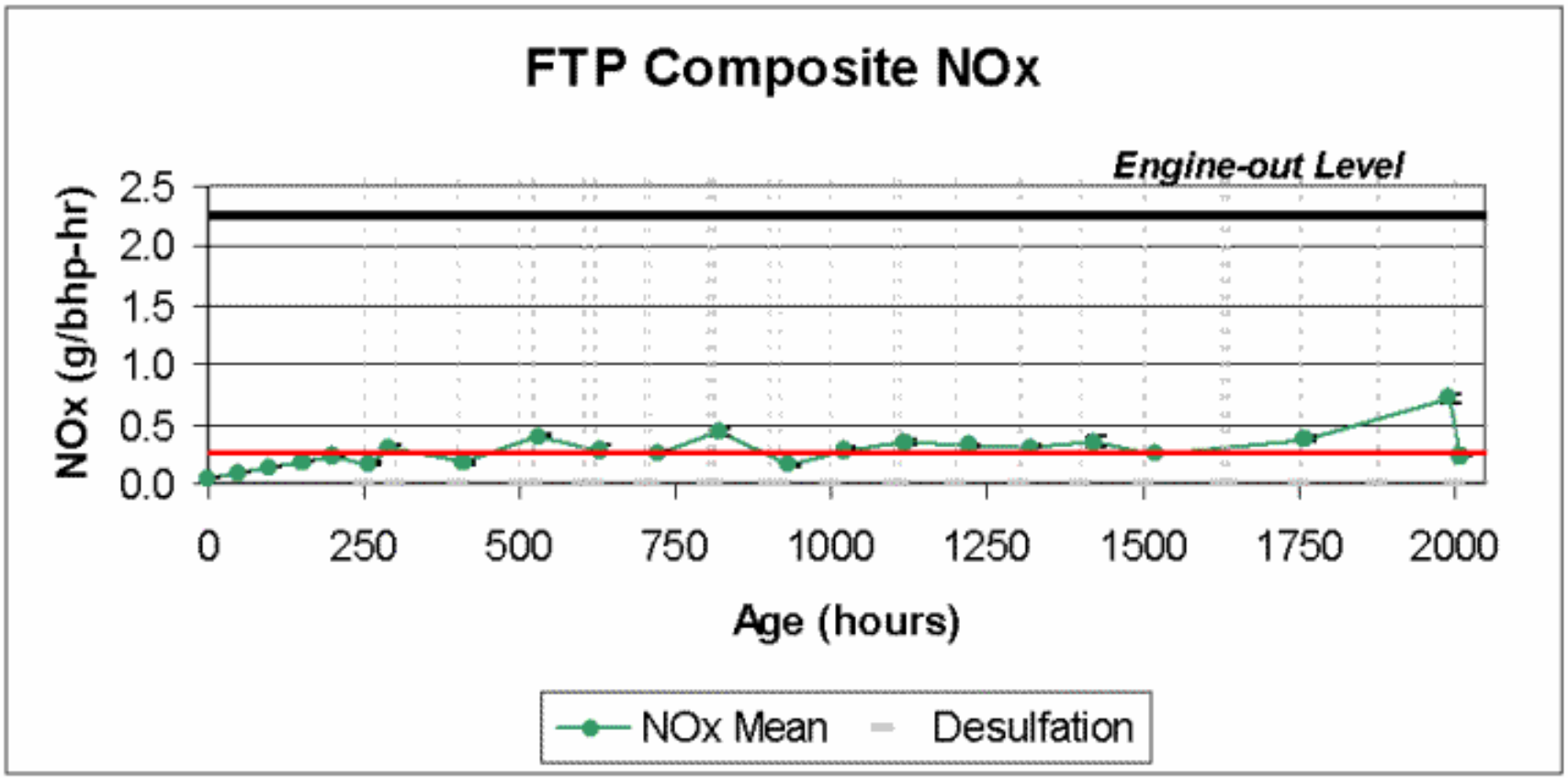
- See SAE 2004-01-0587 for additional information

Catalyst Aging Study

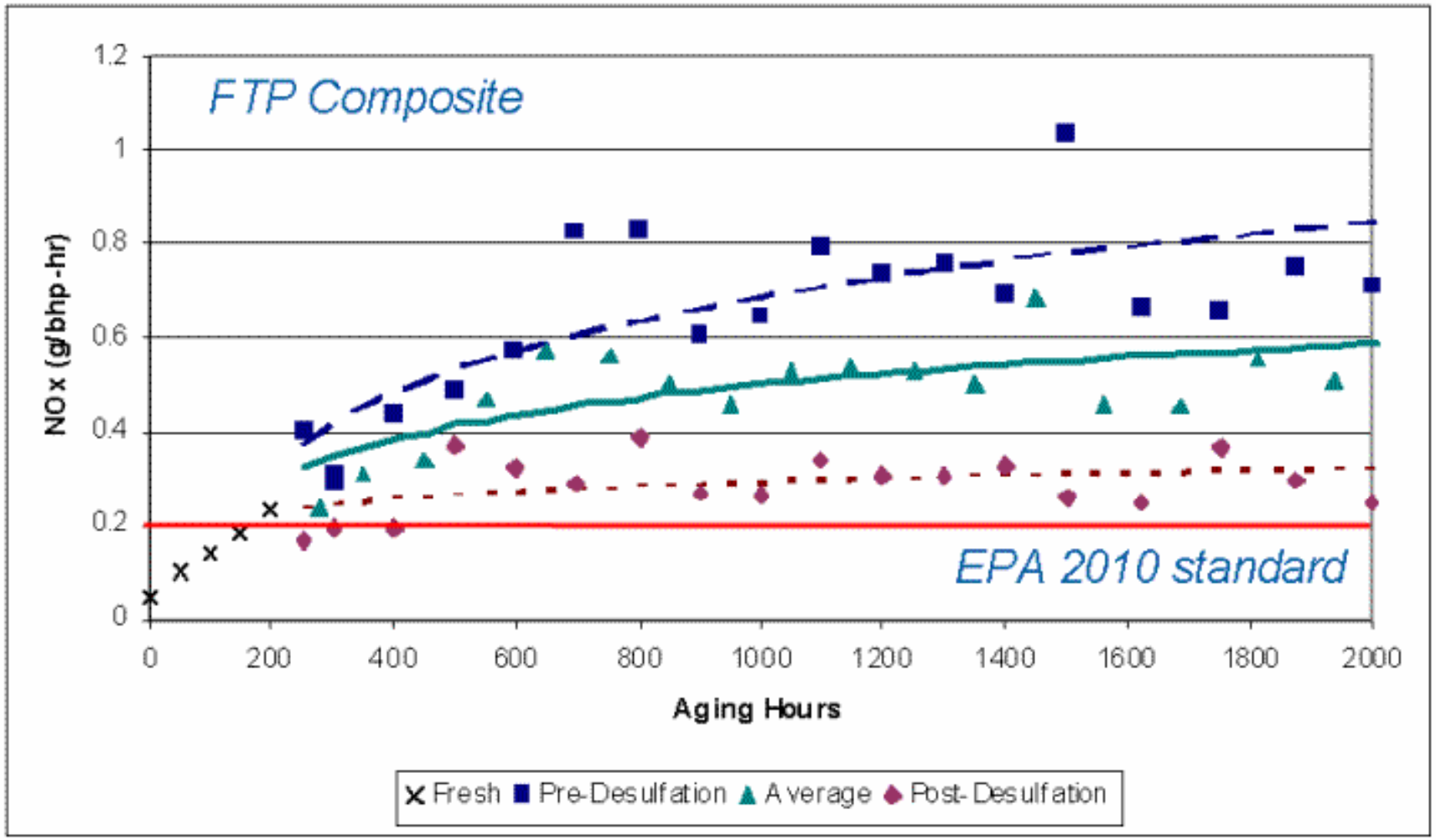
Aging Protocol

- 2000 hour aging test
- Repeated 13-mode test points (2 min.)
  - 49% load factor
- 15-ppm S fuel (DECSE)
- Periodic performance evaluations
  - 50, 100, and 250 hour intervals
  - Selected evaluations for “unregulateds”
  - Conducted after desulfation

Aging Results - NO_x



Trends Analysis - NO_x



Routes to Improved Performance

- More robust control strategy
- Improved catalyst formulation
- Additional sulfur management
- Lower engine-out NOx
  - 0.8-1.0 g/bhp hr

Acknowledgments

- APBF-DEC steering committee and workgroups
- Stephen Goguen and Kevin Stork of the Department of Energy
- Cummins, Inc. for supply of the test engine and related technical support
- MECA for supply of the emission control hardware and technical support
- The team at Ricardo CTC in Burr Ridge, IL
- Joe Kubsh and Dale McKinnon of MECA
- Michael Murphy, John Orban, David Wendt of Battelle Memorial Institute
- Brian West and John Storey of ORNL