Overview of the Experimental Designs, Databases, and Key Findings from the Diesel Emissions Control – Sulfur Effects (DECSE) Program

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Presented at the CLEERS Workshop

Dearborn, MI

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Discussion Topics

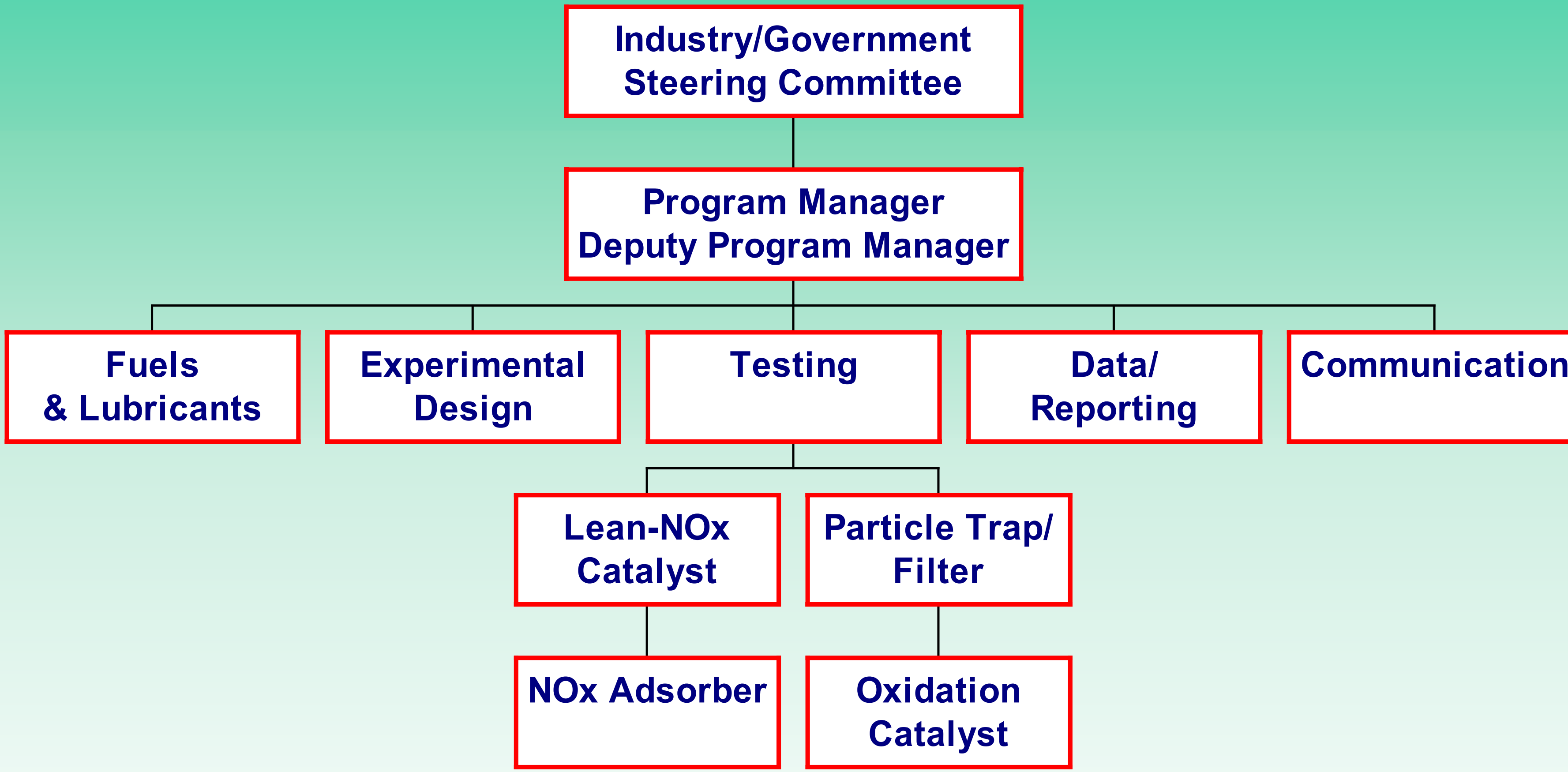
- DECSE Program Background
- DECSE Projects

  (DPF, NO_x Adsorber, DOC/Lean NO_x)
  - Experimental Design
  - Database
  - Key Findings
- Advanced Petroleum-Based Fuels – Diesel Emissions Control (APBF-DEC) Program Overview

DECSE Background - Objective

Determine the impact of fuel sulfur levels on emission control systems that could be implemented to lower emissions of NO_x and PM from on-highway trucks in the 2002-2004 time frame.

DECSE Background - Organization



DECSE Background - Sponsors

- Engine Manufacturers Association
- Manufactures of Emission Controls Association
- U. S. Department of Energy
  - Office of Heavy Vehicle Technologies
  - Office of Advanced Automotive Technologies
  - Laboratories: NREL and ORNL

DECSE Background - Overview

- Emission Control Systems
  - Diesel oxidation catalysts
  - Lean-NO_x catalysts
  - NO_x adsorbers
  - Diesel particle filters
- Fuel Sulfur Levels: 3, 30, 150, 350 ppm
- ECS Aging: Up to 250 hours
- Engines: modern, production engines for source of exhaust

DECSE Background - Project Status

- Diesel Particulate Filters
  - Test Program/Report Completed January 2000
  - Lab: Engineering Test Services – Charleston, SC
- NO_x Adsorbers
  - Phase I (Sulfur Effects) Completed October 1999
  - Phase II (Desulfurization) Completed October 2000
  - Lab: FEV – Auburn Hills, MI
- Diesel Oxidation Catalysts/Lean-NO_x Catalysts
  - Test Program/Report Completed June 2001
  - Lab: West Virginia University

DECSE Emissions Data

Engine	Test Method	Catalyst Age (hrs)	Fuel Sulfur (ppm)	Emissions Measured[1]	
				Gases and Fuel Economy[2]	Particulate Matter[3]
Cummins ISM370	OICA modes 2, 3, 10, 11	0, 50, 150, 250	3, 30, 150, 350	EO, DOC, LNOx	
	OICA 4-mode wtd.	0, 50, 150, 250	3, 30, 150, 350	EO, DOC, LNOx	EO, DOC, LNOx
	OICA mode 2 (w/ filter)	0	3, 30, 150, 350	EO, DOC, LNOx	EO, DOC, LNOx
	FTP hot	0, 50, 150, 250	3, 30, 150, 350	EO, DOC	EO, DOC
Navistar T444E	Nav-9 modes 2, 3, 7, 9	0, 50, 150, 250	3, 30, 150, 350	EO, DOC, LNOx	
	Nav-9 (4-mode) wtd.	0, 50, 150, 250	3, 30, 150, 350	EO, DOC, LNOx	EO, DOC, LNOx
	Nav-9 mode 9 (w/ filter)	0	3, 30, 150, 350	EO, DOC, LNOx	EO, DOC, LNOx
	FTP 75	0, 50, 150, 250	3, 30, 150, 350	EO, DOC	EO, DOC
Caterpillar 3126	OICA modes 1-13	Note[4]	3, 30, 150, 350	EO, CDPF, CRDPF	
		Note[4]	30	EO, CDPF, CRDPF	
	OICA 13-mode wtd.	Note[4]	3, 30, 150, 350	EO, CDPF, CRDPF	EO, CDPF, CRDPF
		Note[4]	30	EO, CDPF, CRDPF	EO, CDPF, CRDPF
	OICA mode 2 (w/ filter)	Note[4]	3, 30, 150, 350	EO, CDPF, CRDPF	EO, CDPF, CRDPF
	OICA mode 4 (w/ filter)	Note[4]	3, 30, 150, 350	EO, CDPF, CRDPF	EO, CDPF, CRDPF
1.9L HSDI prototype	Performance mapping @ 3000 rpm over range of temperatures	Up to 250	3, 16, 30, 78	EO, NAC	EO, NAC

[1] Entries identify source from which emissions data were obtained for each combination of catalyst/filter age and fuel sulfur level.
EO = Engine-out; DOC = Diesel Oxidation Catalyst; LNOx = Lean NOx Catalyst; CDPF = Catalyzed Diesel Particulate Filter; CRDPF = Continuously Regenerating Diesel Particulate Filter, NAC = NOx Adsorber Catalyst

[2] HC, NOx, CO, CO2, BSFC

[3] Total PM, SOF, SO4, NO3

[4] The same CDPF and CRDPF filters were used throughout the test program. The 30-ppm sulfur fuel was tested after approximately 100 hours and 425 hours of use to evaluate aging effects.

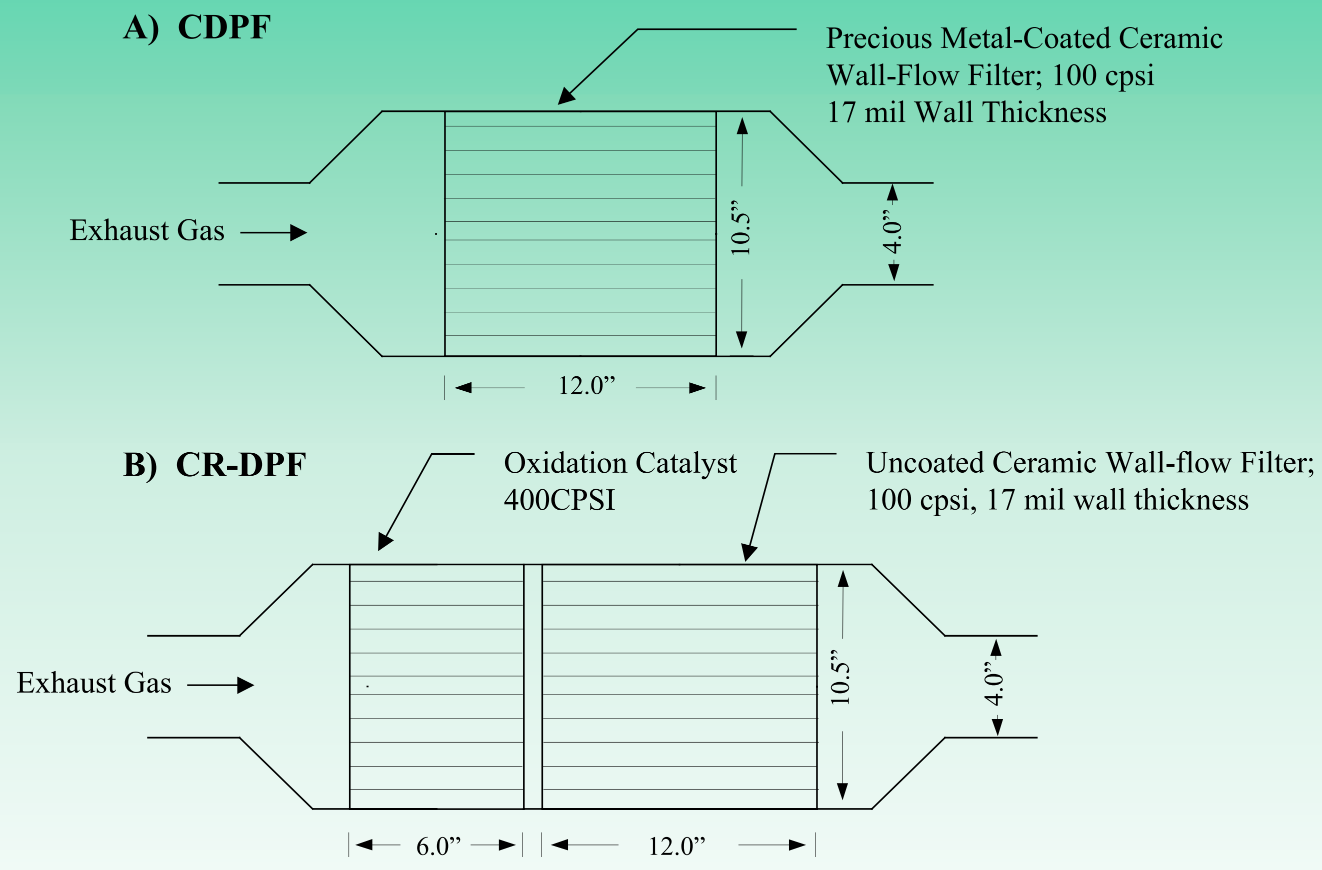
DECSE Background – Web Site

- http://www.ott.doe.gov/decse
  - Project Final Reports
  - Program Summaries
  - Fact Sheet
  - Questions and Answers about DECSE
  - Contacts

Diesel Particulate Filter Project

- Final Report Date: January 2000
- Lab: Engineering Test Services
- Test Engine: Caterpillar 3126

DPF Systems



A) CDPF
Precious Metal-Coated Ceramic
Wall-Flow Filter; 100 cpsi
17 mil Wall Thickness
Exhaust Gas
10.5”
4.0”
12.0”
B) CR-DPF
Oxidation Catalyst
400CPSI
Uncoated Ceramic Wall-flow Filter;
100 cpsi, 17 mil wall thickness
Exhaust Gas
10.5”
4.0”
6.0”
12.0”

DPF Study Questions

- How does DPF affect emissions of PM (including SO_2, SOF, NO_3) and selected gases?
- How does fuel sulfur affect emissions (both engine-out and post-filter)?
- Does DPF performance degrade over time?
- How does fuel sulfur affect the Balance Point (regeneration) Temperature (BPT)?
- Other related questions

DPF Performance Tests

- Emissions Tests
  - Triplicate OICA 13-mode
    - Gases – by mode
    - TPM, SOF, SO_4
  - Duplicate Steady-State Tests
    - Gases, TPM, SOF, SO_4
    - “Peak-Torque” OICA Mode 2
    - “Road-Load” OICA Mode 4
- Balance Point (Regeneration) Temperature Tests
  - Triplicate “5-mode” tests at each of 3 speeds and 5 temperatures
  - Confirmatory tests at constant temperatures

DPF Experimental Design

Test	Fuel Sulfur Level (ppm)				
	3	30	150	350	30
Emissions Tests	EO (x2/x3) CDPF, CR-DPF (x2/x3)	EO (x2/x3) CDPF, CR-DPF (x2/x3)	EO (x2/x3) CDPF, CR-DPF (x2/x3)	EO (x2/x3) CDPF, CR-DPF (x2/x3)	EO (x2/x3) CDPF, CR-DPF (x2/x3)
5-mode BPT Test	5 temp, 3 speeds (x3)	5 temp, 3 speeds (x3)	5 temp, 3 speeds (x3)	5 temp, 3 speeds (x3)	
Constant Temp Test	T1,T2, T3, T4	T1*, T2*	T1*, T2*	T1*, T2*	

Design of BPT Tests

- Three Key Test Parameters
  - Engine Speed
  - Engine Exhaust Temperature
  - Engine Torque
- Balance Point Temperature (BPT) determined by measuring change in exhaust pressure (delta-P) across device at different temperatures
  - Decreasing delta-P indicates filter regeneration (PM combustion rate greater than build-up rate)

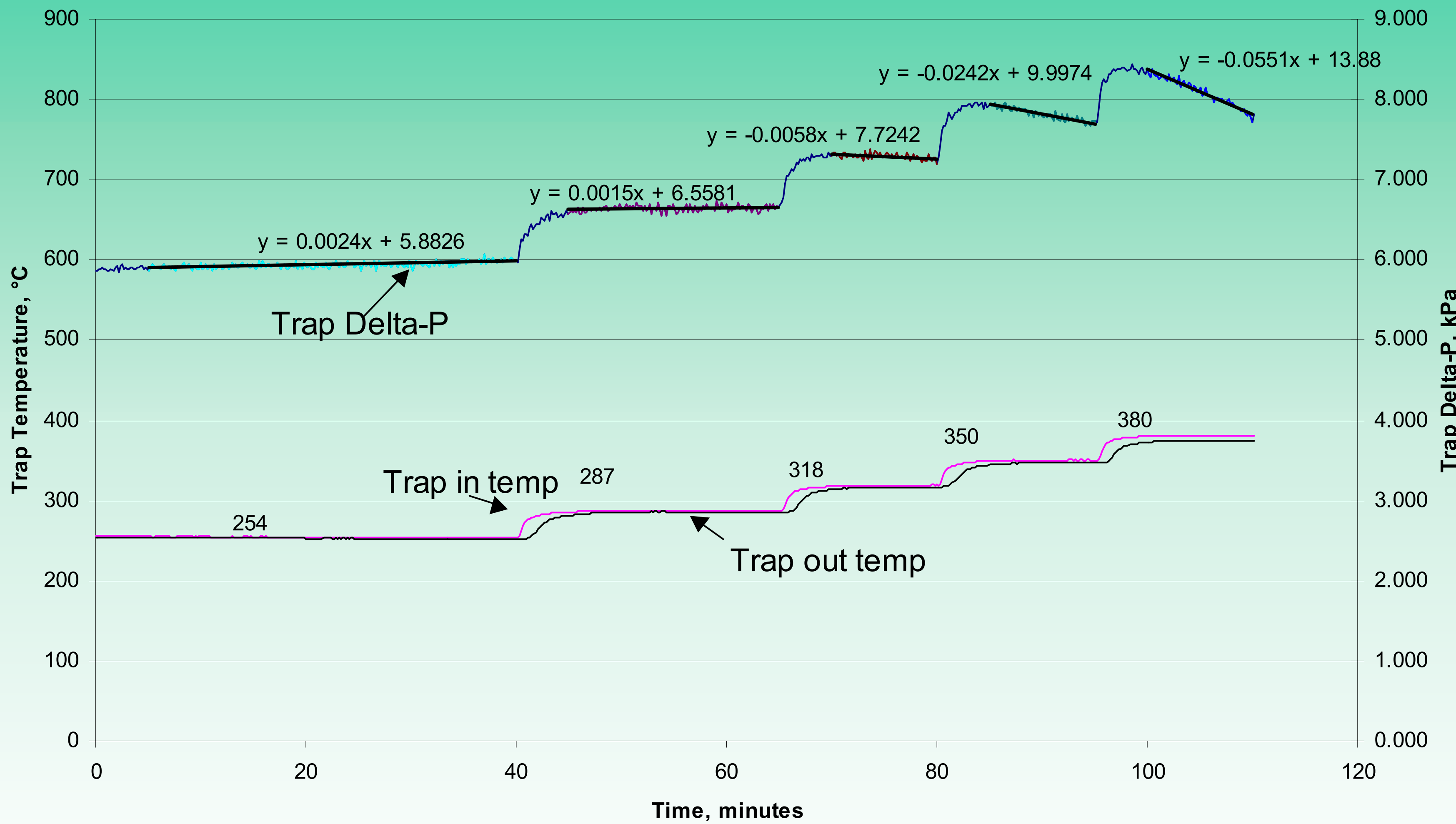
Three Test Methods Considered

(Exhaust temperature and delta-P measured for each)

- 5-Mode BPT Test (primary method)
  - Hold speed fixed. Increase torque to achieve 5 specified temperatures. Hold for 15 minutes.
- Constant Temperature Test (confirmatory method)
  - Hold temperature fixed. Vary torque to achieve three engine speeds for 20 minutes each. Repeat ten times.
- Ramp Test (not used)
  - Hold speed fixed. Increase torque continuously causing temperature to increase.

5-Mode BPT Test

(constant speed - 5 torque/temperature settings)



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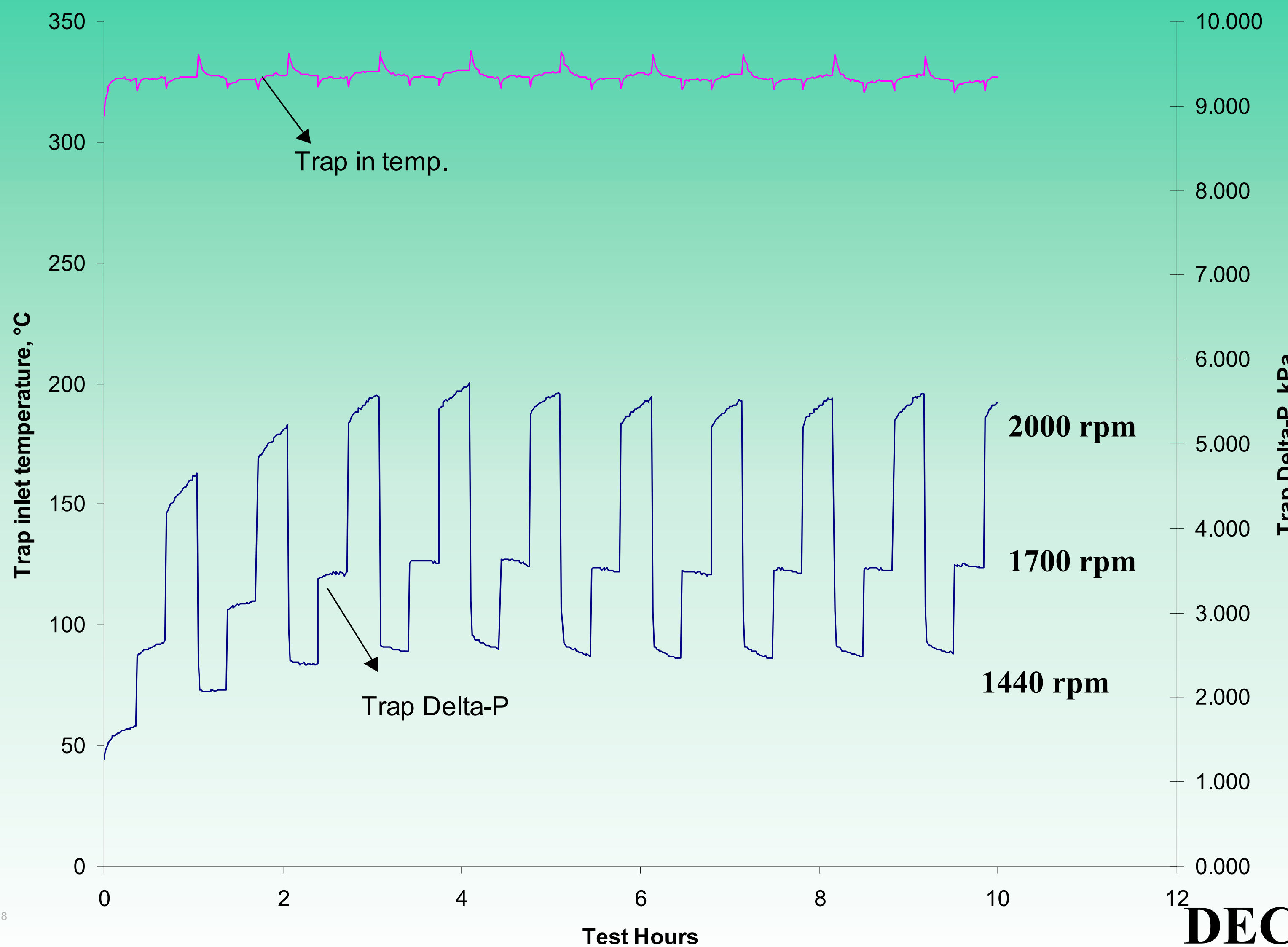
Constant Temperature Test
(change speed every 20 minutes)



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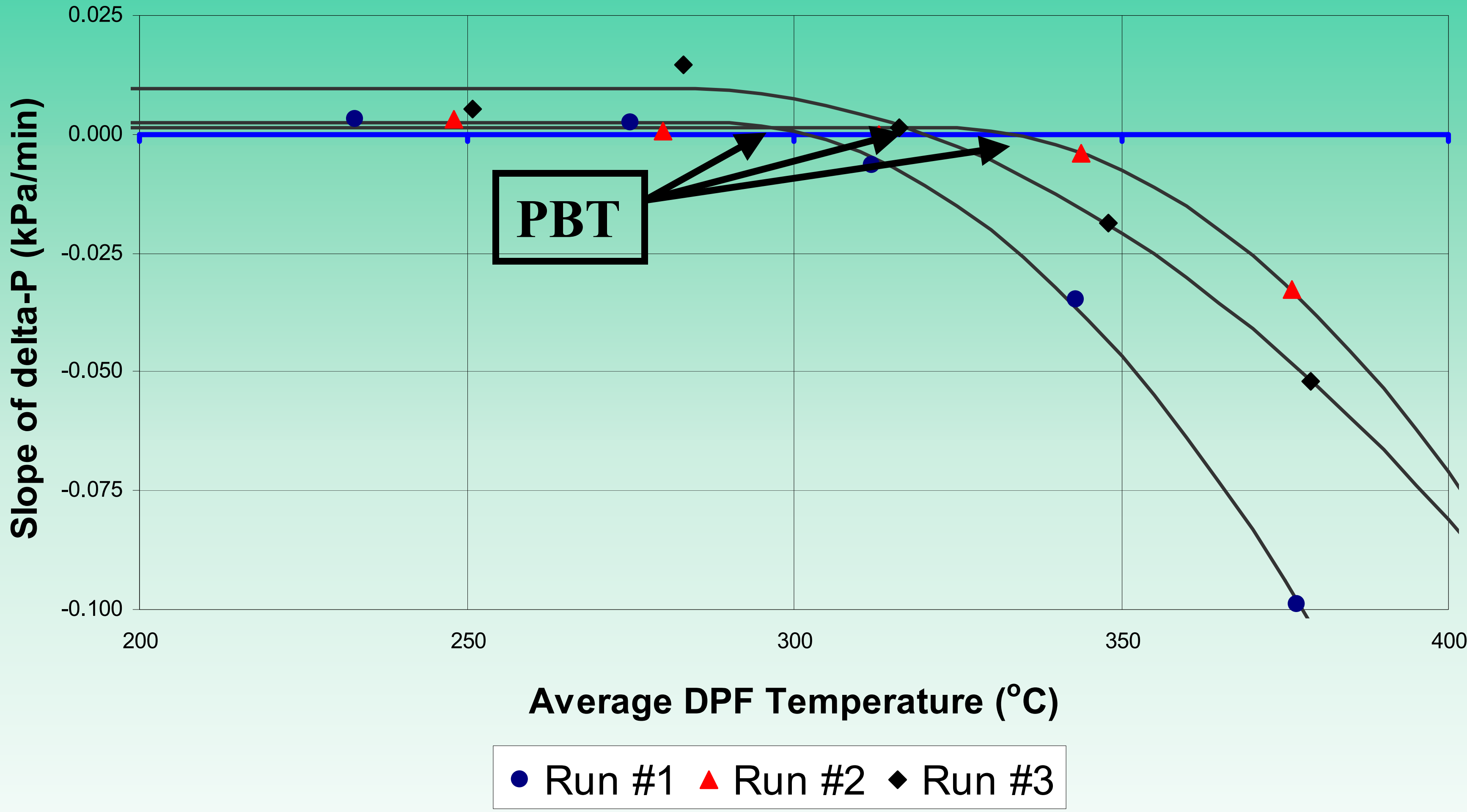
Sample Results (5-mode tests)



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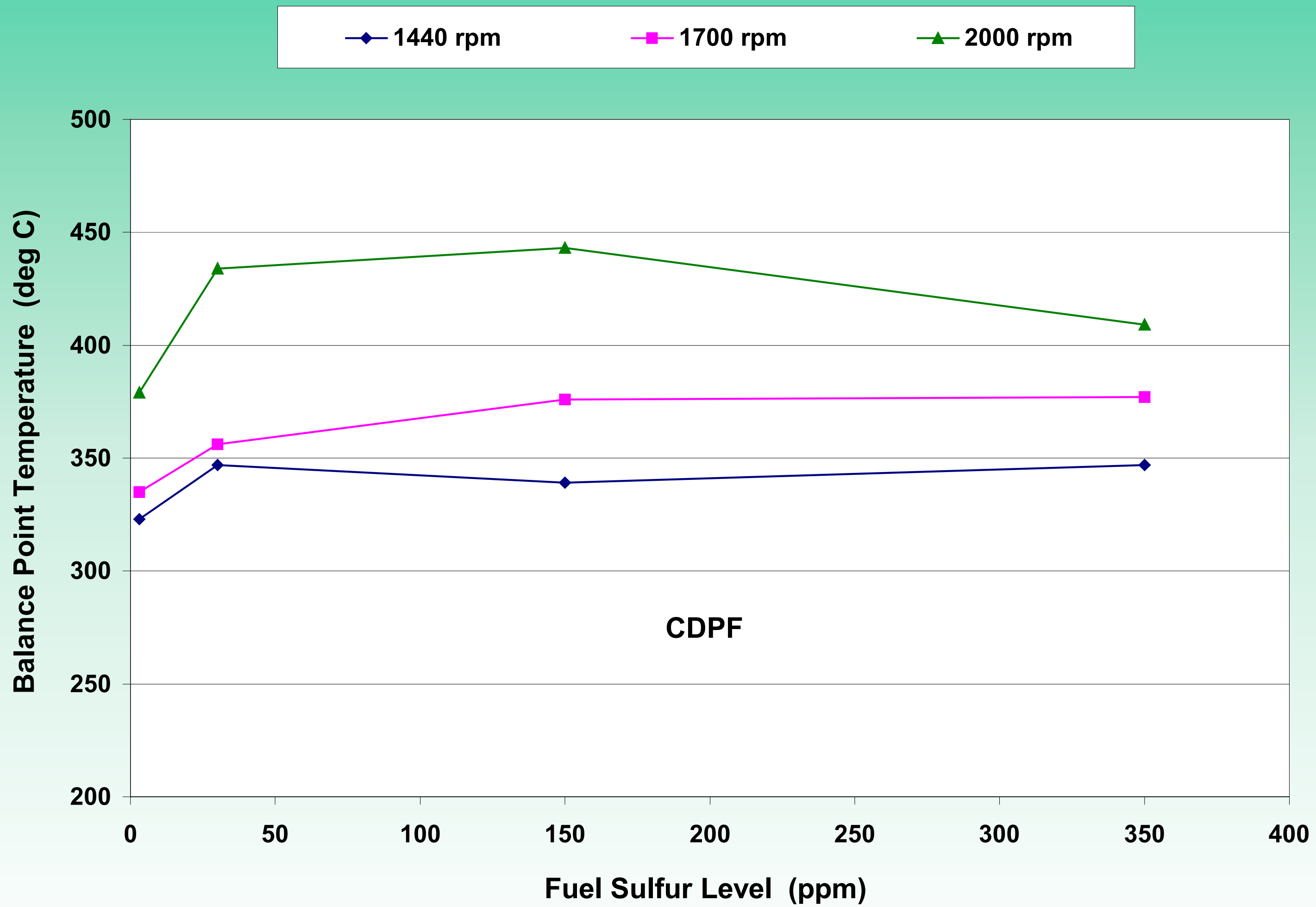
BPT Estimates (with 95% confidence intervals)

Engine Speed (rpm)	Estimate	Fuel Sulfur Level (ppm)			
		3	30	150	350
1,440	BPT[1]	323 (<344)	349 (340, 357)	334 (<362)	347 (<400)
	ΔBPT[2]		25 (2, 48)	11 (-24, 46)	24 (-33, 81)
1,700	BPT	337 (323, 348)	344 (<367)	376 (355, 395)	377 (365, 387)
	ΔBPT		7 (-19, 33)	39 (15, 63)	39 (22, 56)
2,000	BPT	380 (>350)	435 (427, 442)	426 (407, 441)	409 (399, 418)
	ΔBPT		56 (25, 87)	47 (13, 81)	30 (-1, 61)

[1] BPT estimated from pooled data
[2] Change in estimated BPT compared to 3-ppm test

Balance Point Temperature - DPF



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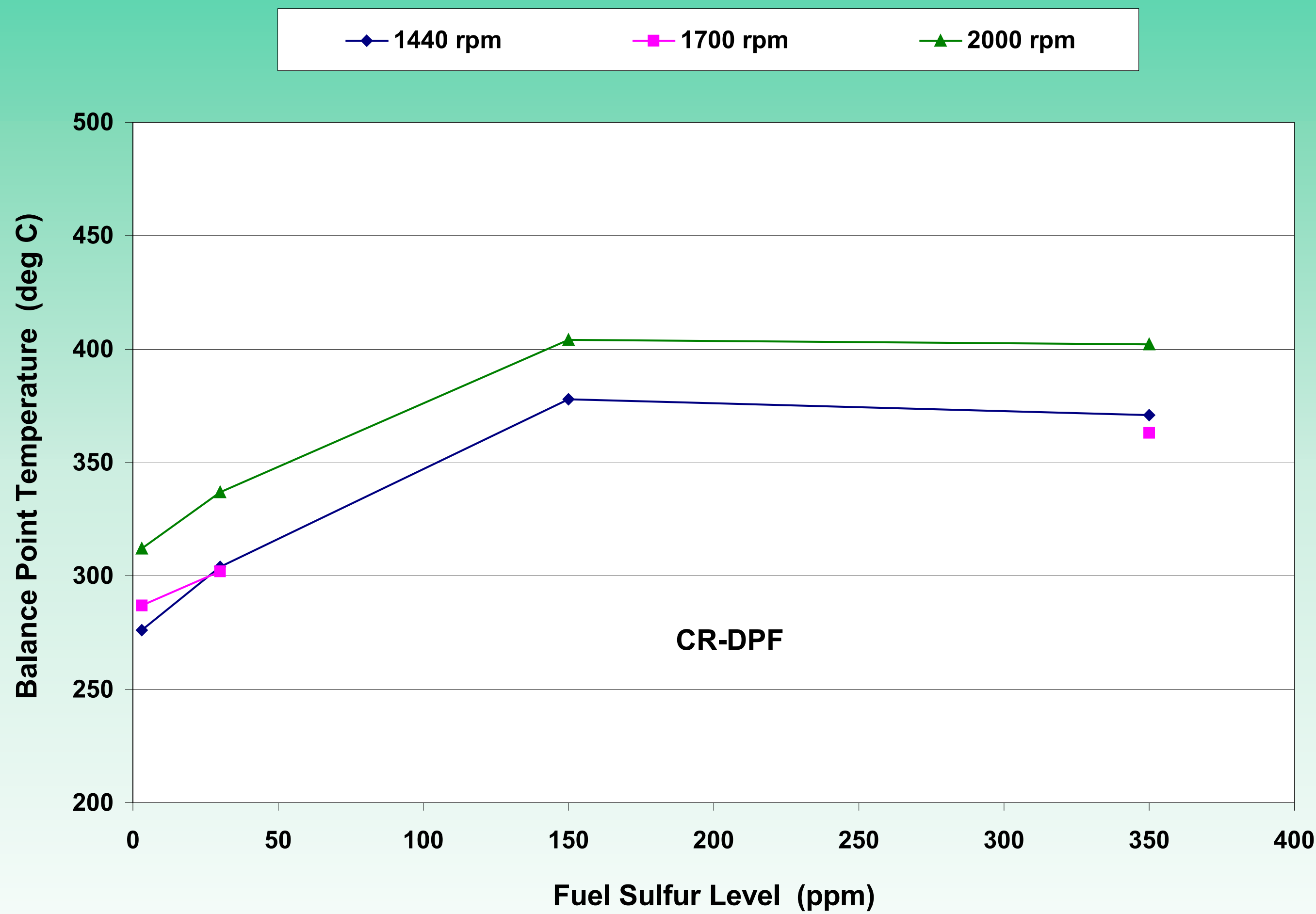
Balance Point Temperature - CR-DPF



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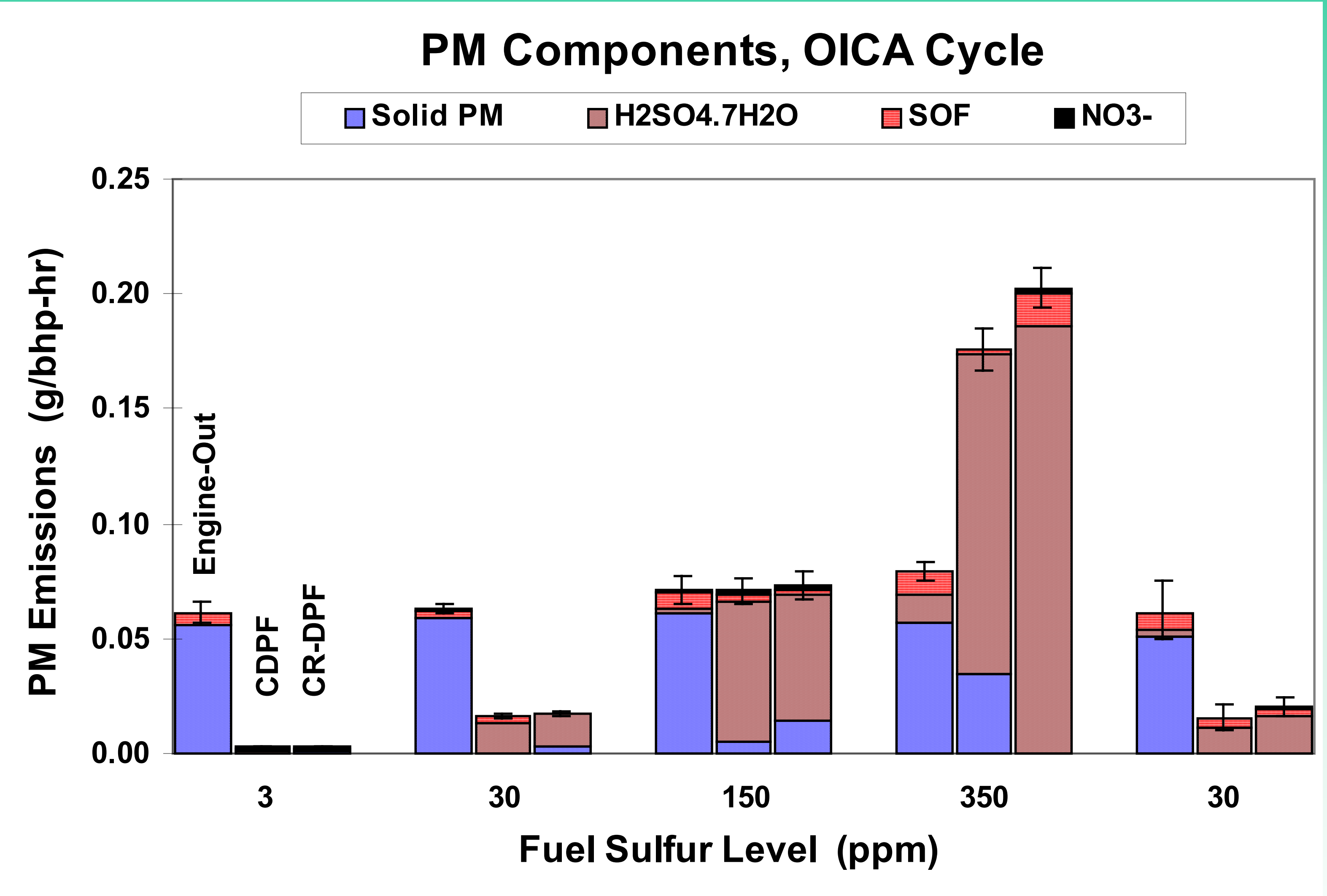
Effects of Fuel Sulfur on PM Emissions



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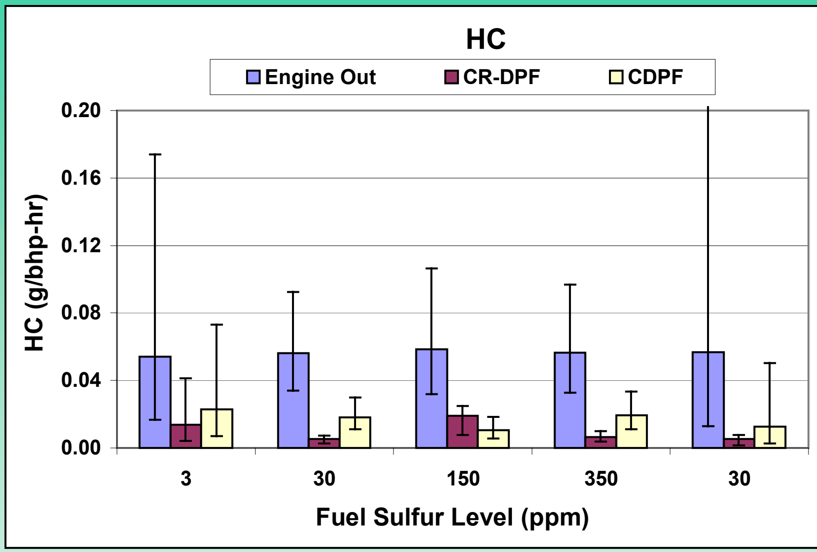
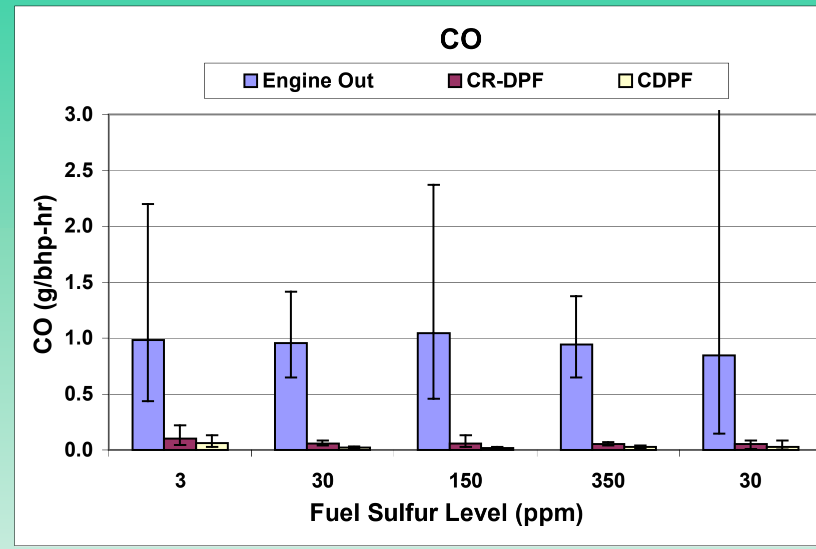
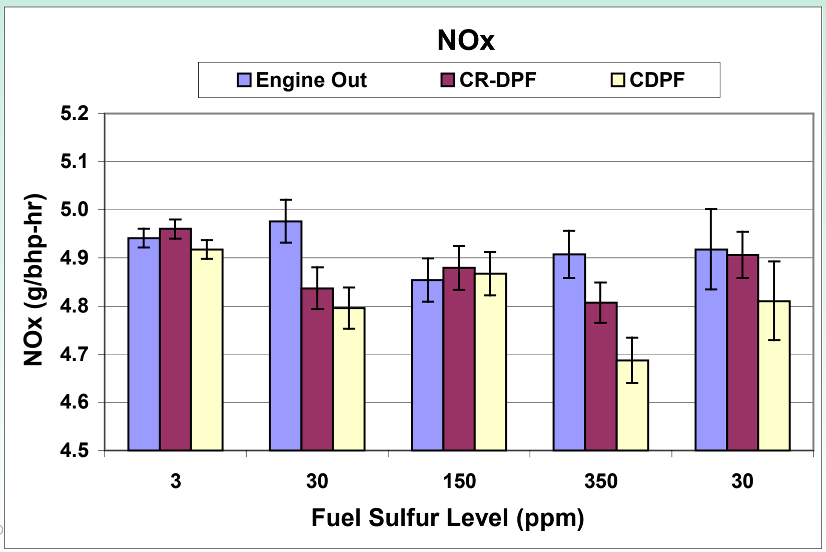
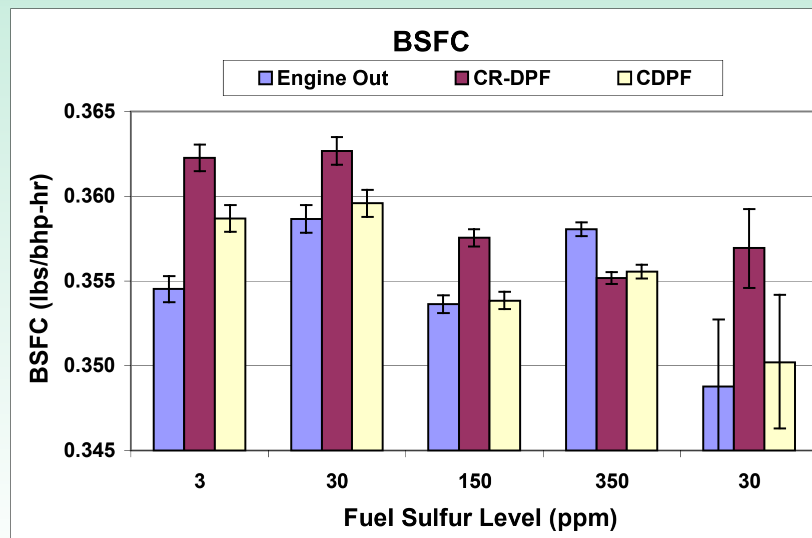
DPF Gaseous Emissions









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DPF Key Findings

- Both DPF Technologies Reduce PM Emissions by 95% When Used with Low (3-ppm) Sulfur Fuel
- DPF Regeneration Temperatures Increase by 25 deg C When Changing from 3-ppm to 30-ppm Sulfur Fuel
- Fuel Sulfur Produces a Significant Increase in Post DPF PM Emissions Due to SO_4 Formation (40% to 60% Conversion of Fuel Sulfur)
- DPF Technologies Reduce HC by 70% to 90% and CO by 90% to 99%, Depending on Test Mode and Technology

NO_x Adsorber Catalyst Project

- Final Report Date: October 2000
- Lab: FEV
- Test Engine: 1.9L HSDI Prototype

NO_x Adsorber Tasks

- Develop/Improve Calibration to Achieve Maximum NO_x Conversion
- Map Performance
- Develop Desulfurization Process
- Demonstrate Desulfurization
- Evaluate Performance During Repeated Aging/Desulfurization Cycles

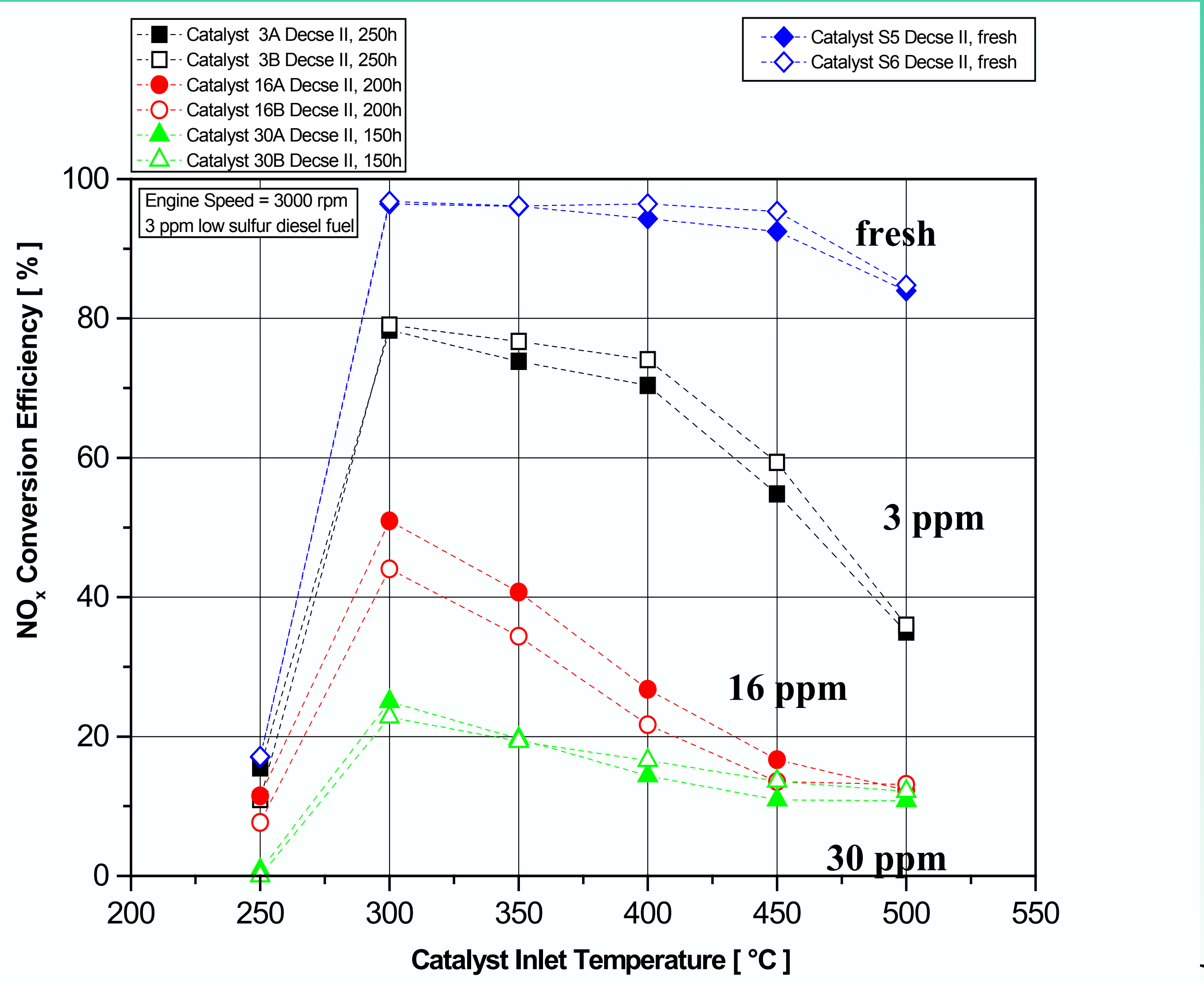
Test Summary

Test Purpose	Catalyst	Sulfur I (ppm)	Comments
Task 1: Degreening, Initial Aging	S3, S4 S5, S6, S7, S8	3	S3 & S4 aged 75 hours, all others aged 10 hours
Task 2: Improve calibration to maximize NO_x conversion	S4	3	
Task 3: Performance mapping	S4, S5, S6 3a, 3b, 16a, 16b, 30a, 30b	3	
Task 4: Develop desulfurization process	S4 (process dev.) S3 (process check)	3, 380	3-ppm used for desulfurization 380-ppm using for poisoning
Task 5: Desulfurization demo/ Performance map	3a, 3b, 16a, 16b, 30a, 30b	3, 150 3	3-ppm used for desulfurization 150-ppm using for poisoning; Phase 1 cats desulfurized from current state, no add'l poisoning
Task 6a: Periodic re-evaluation (10 hour aging, map, desulfurization, map: complete 5 cycles)	S5, S6 S7, S8	3 75, 3	S5, S6 all testing with 3-ppm; S7, S8 aging with 75-ppm, desulfurization with 3-ppm
Task 6b: Characterize performance trends (multiple desulfurizations, map: complete 5 cycles)	S7, S8	3	12 desulfurizations were completed between each performance mapping

Key Findings

- Improved lean/rich engine calibration achieved NO_x conversion efficiencies exceeding 90% over catalyst inlet operating temperatures from 300°C to 450°C.
- Desulfurization procedure showed recovery to greater than 85% NO_x conversion efficiency in catalysts exposed to 3-, 16-, and 30-ppm sulfur fuel for up to 250 hours over 300°C to 450°C range after single desulfurization event.
- Desulfurization procedure developed has the potential to meet in-service engine operating conditions and provide acceptable driveability conditions.

NO_x Conversion Efficiency Results
(fresh and aged catalysts)



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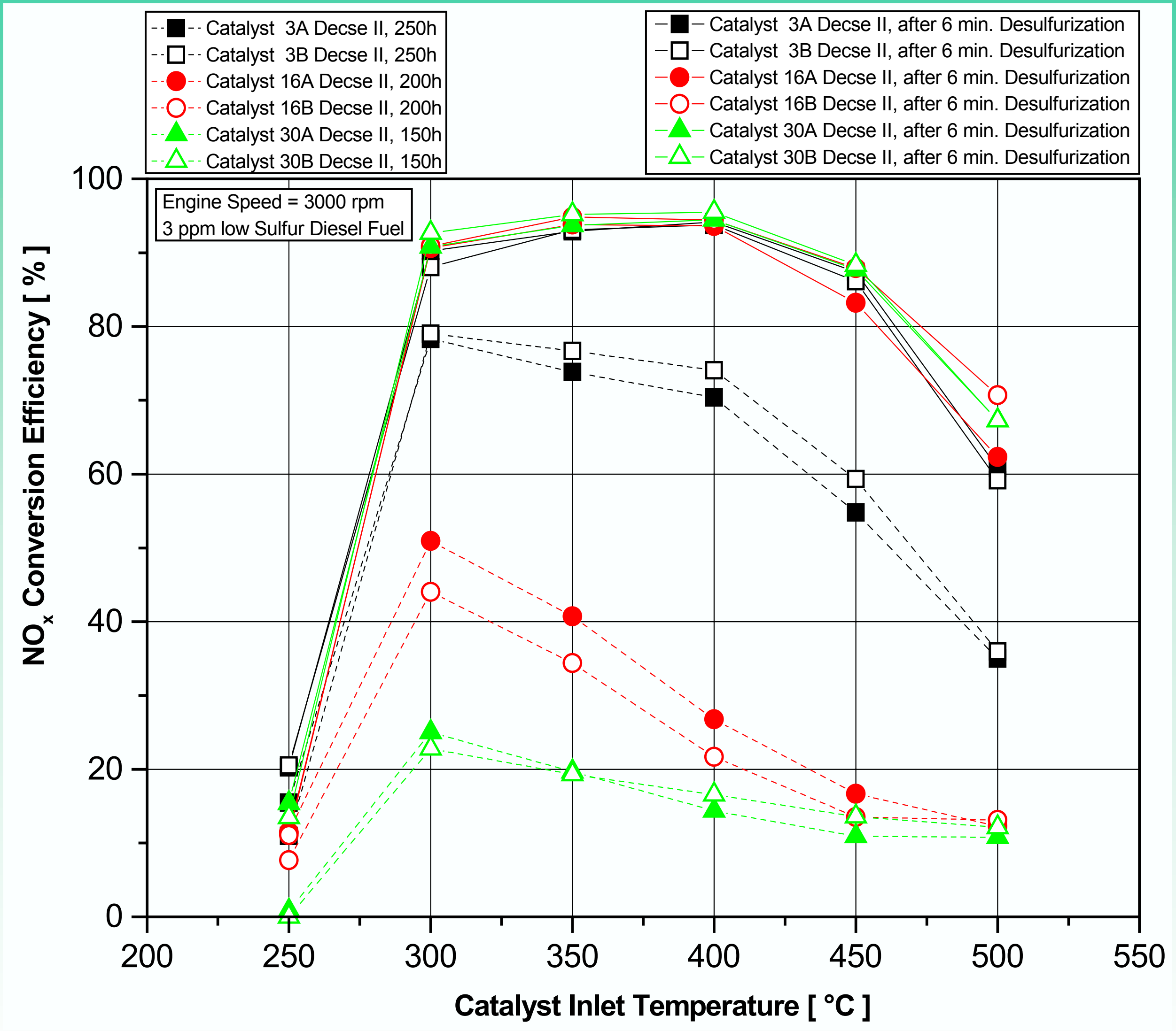
Recovery of NO_x Conversion Following Desulfurization



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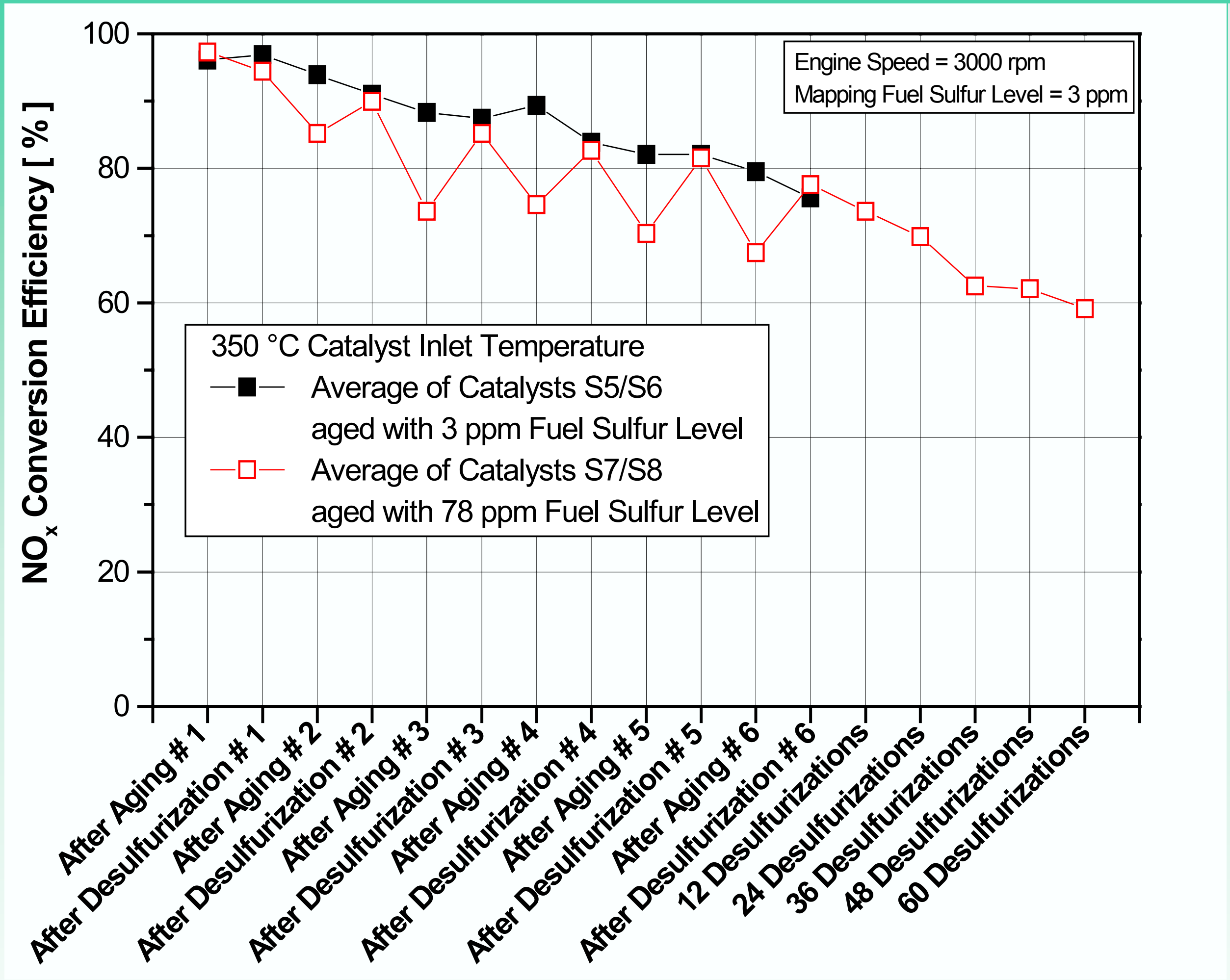
Key Findings (continued)

- Aging with 78-ppm sulfur fuel reduced NO_x conversion efficiency more than aging with 3-ppm sulfur fuel, but desulfurization events restored the conversion efficiency to nearly the same level of performance. Repeatedly exposing the catalyst to the desulfurization procedure caused a continued decline in the catalyst's desulfurized performance.

- Rate of sulfur contamination increased with repeated desulfurization cycles when using 78-ppm sulfur fuel. This was not observed with 3-ppm sulfur fuel.

Influence of Aging with Higher Sulfur Levels



- Series of single desulfurization events with 10 hour aging between (3-ppm or 78-ppm sulfur fuel for aging), performance mapped following each aging and each desulfurization
- Series of multiple desulfurization events followed by performance maps

NO_x Adsorber Data Available on CD

- Contact Helen Latham
  - lathamh@battelle.org
  - (614) 424-4062
- Includes
  - Final Report
  - Monthly Lab Reports
  - Gaseous Data Files (Tasks 2-6)
  - Data Documentation

Diesel Oxidation Catalyst/ Lean NO_x Catalyst Project

- Final Report Date: June 2001
- Lab: West Virginia University
- Test Engines:
  - Cummins ISM370
  - Navistar T444E

DOC/Lean NO_x Study Questions

- How does the Catalyst affect emissions of NOx, HC, CO, and PM? (EO vs. Post Cat)
- How does the sulfur level in the fuel affect Post Cat emissions (relative to EO)? (at age zero)
- How does catalyst age (without sulfur) affect Cat performance?
- What is the effect of sulfur during aging on Cat performance? Total ppm hrs or other relationship?

DOC/Lean NO_x Study Questions (continued)

- Can the Cat recover from the effects of high sulfur levels? By how much? How quickly?
- How does Cat performance vary as a function of engine operating conditions (temperature)?
- How does this relationship change as a function of age and fuel sulfur level?

Emissions Tests

Catalyst	Engine	Test Mode
DOC	Navistar T444E	Modes 2, 3, 7 and 9 from Nav-9 High exhaust temperature Nav-9 mode 9 FTP hot-cycle
	Cummins ISM370	Modes 11, 3, 10 and 2 from OICA-13 High exhaust temperature OICA-13 mode 2 FTP75 mimicry
Lean-NO_x	Navistar T444E	Modes 2, 3, 7 and 9 from Nav-9 High exhaust temperature Nav-9 mode 9
	Cummins ISM370	Modes 11, 3, 10 and 2 from OICA-13 High exhaust temperature OICA-13 mode 2

Lean-NO_x Inlet Temperatures

Lean-NO_x Catalyst	Engine	Test Mode	Catalyst Inlet Temperature (°C)
LT	Navistar T444E	Nav-9 Mode 2	135
		Nav-9 Mode 3	207
		Nav-9 Mode 7	247
		Nav-9 Mode 9	405
HT	Cummins ISM370	OICA-13 Mode 11	273
		OICA-13 Mode 3	380
		OICA-13 Mode 10	448
		OICA-13 Mode 2	528

Experimental Design

Aging Hours	Fuel Sulfur Level (ppm)				
	3	30	350	30	150
0	EO[1], C1[2]	EO, C2	EO, C4	EO, C4[3]	EO, C3
50	C1	C2	C4	C4	C3
150	C1	C2	C4	C4	C3
250	EO, C1	EO, C2, C1[4]	EO, C4, C1	EO, C4, C1	EO, C3, C1

(1) Engine-out emissions tests
(2) Post-catalyst emissions tests performed with catalysts C1-C4 (Identical design for high- and low-temperature DOC and Lean NO_x catalyst systems)
(3) 30-ppm recovery tests performed on catalyst C4 following 250 hours of aging with 350-ppm sulfur fuel.
(4) Catalyst C1 was re-tested with 30-, 150-, and 350-ppm sulfur fuel after (thermal) aging for 250 hours with 3-ppm sulfur fuel

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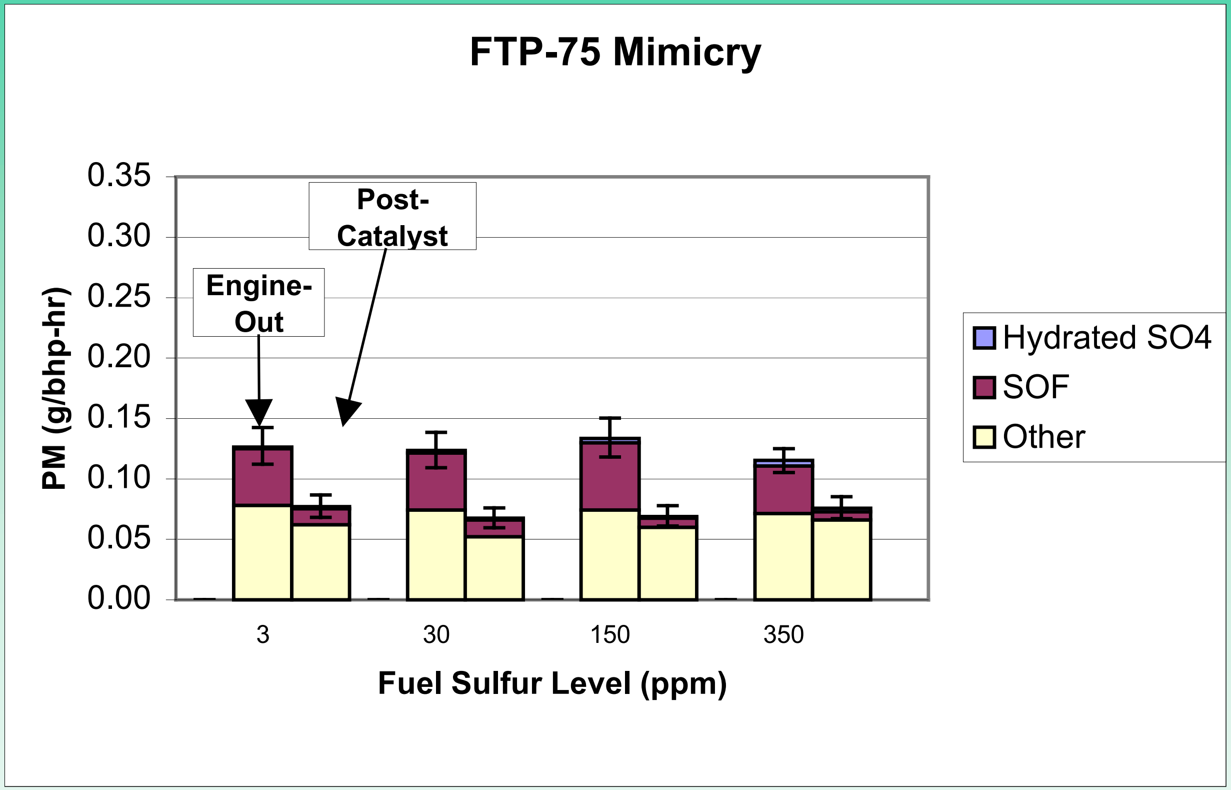
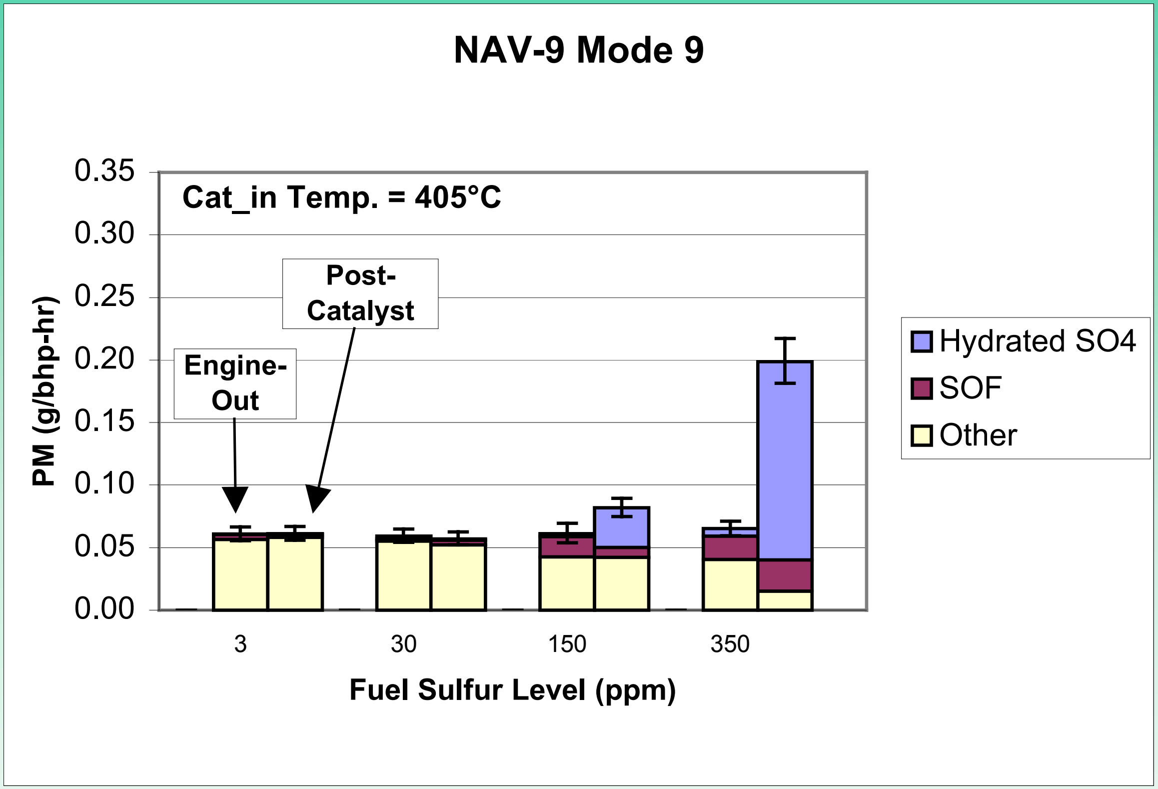
DOC Key Findings

- 90% -100% HC Reduction Efficiency
- 88% - 99% CO Reduction Efficiency
- Low Temp. DOCs (on T444E) Were Effective at PM Reduction Under Transient Tests
- Fuel Sulfur Results in Significant Increase in SO_4 Emissions Under Steady-State Conditions – Especially at Peak Torque
- Sulfur Effects on PM Increase with DOC Age

Effective SOF Reduction with Low Temperature Applications



Increased SO_4 Emissions with High Sulfur Fuel – at Peak Torque



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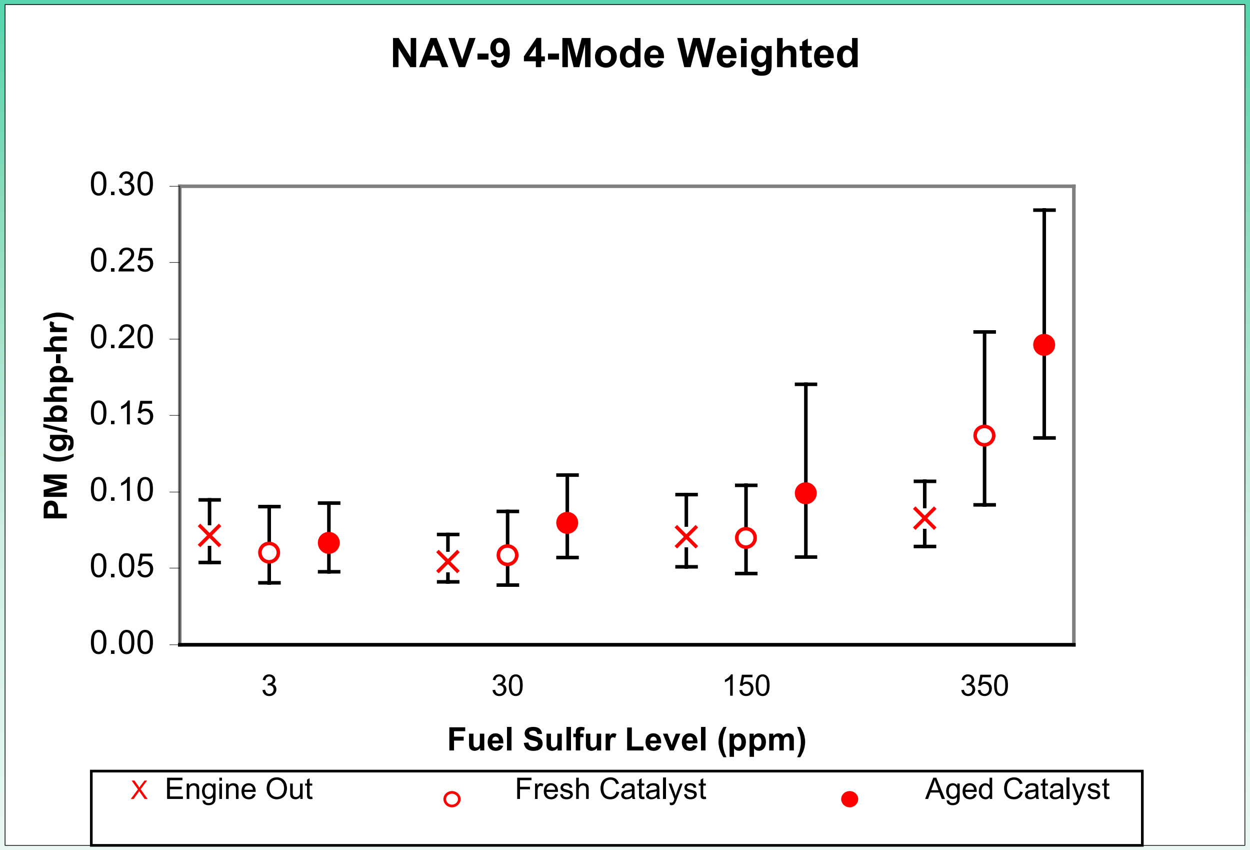
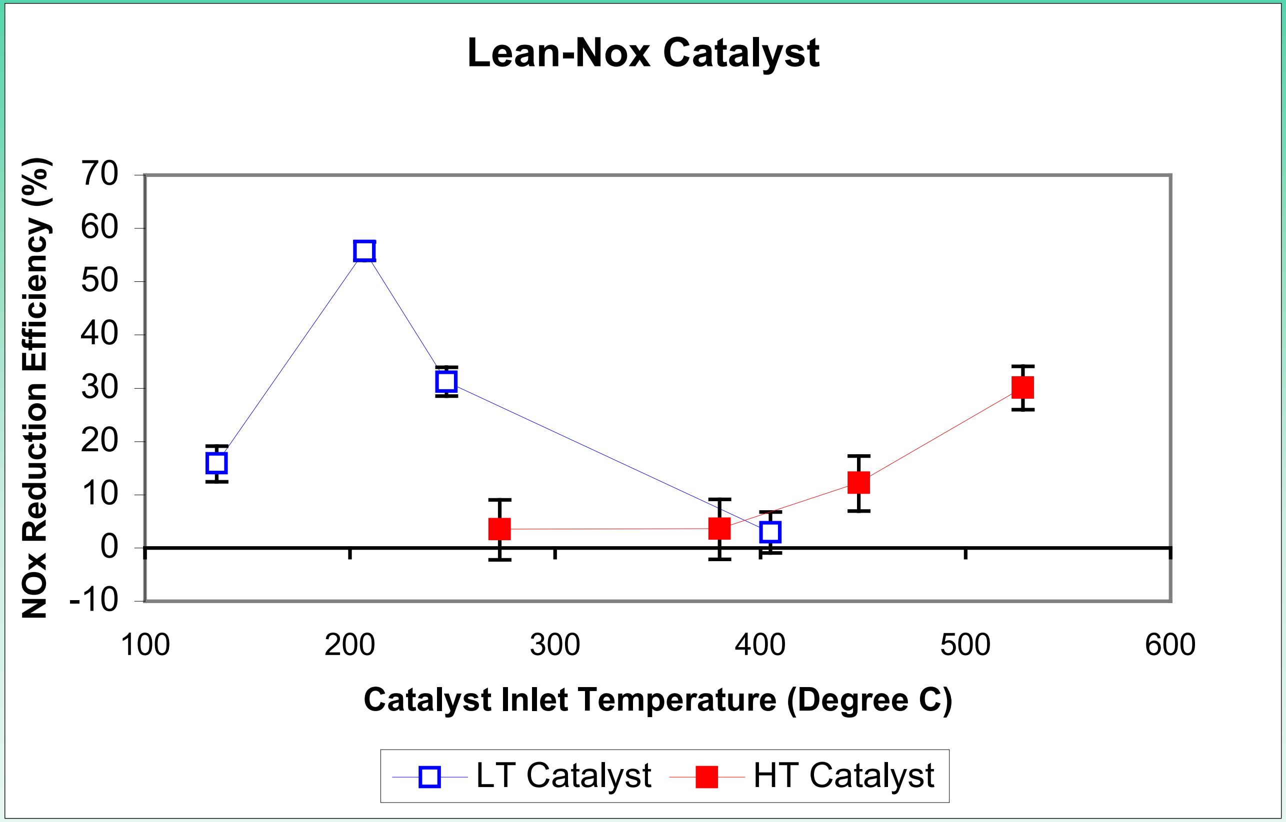
PM (SO_4) Increases with Catalyst Age



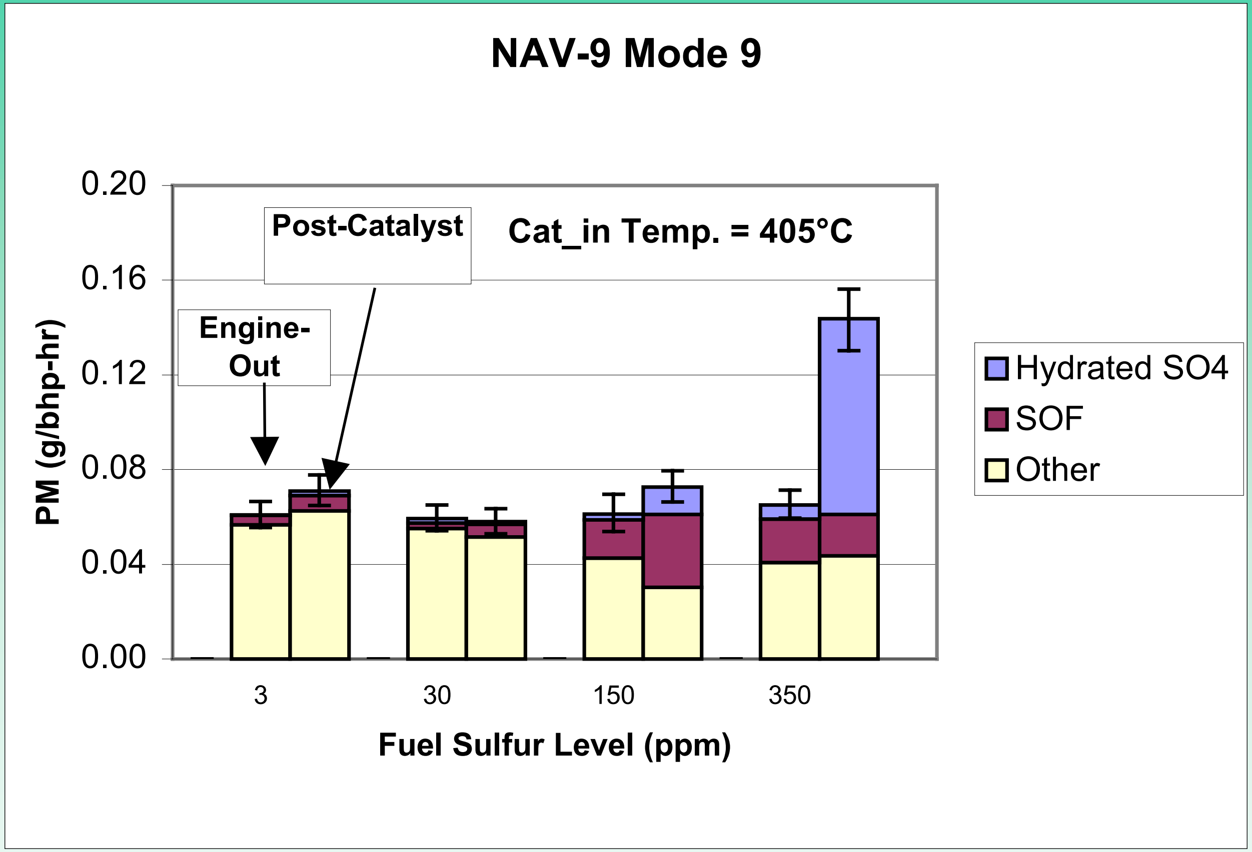
Lean NO_x Key Findings

- Achieved 10% to 50% NO_x Reduction Over Specific Operating Conditions
- Fuel Sulfur Results in Significant Increase in SO_4 Emissions Under Steady-State Conditions – Especially at Peak Torque
- High Temperature LNCs (on ISM370) are vulnerable to HC slip
- Sulfur Effects on PM Increase with LNC Age

NO_x Reduction vs. Engine Temp.



Increased SO_4 Emissions with High Sulfur Fuel – at Peak Torque



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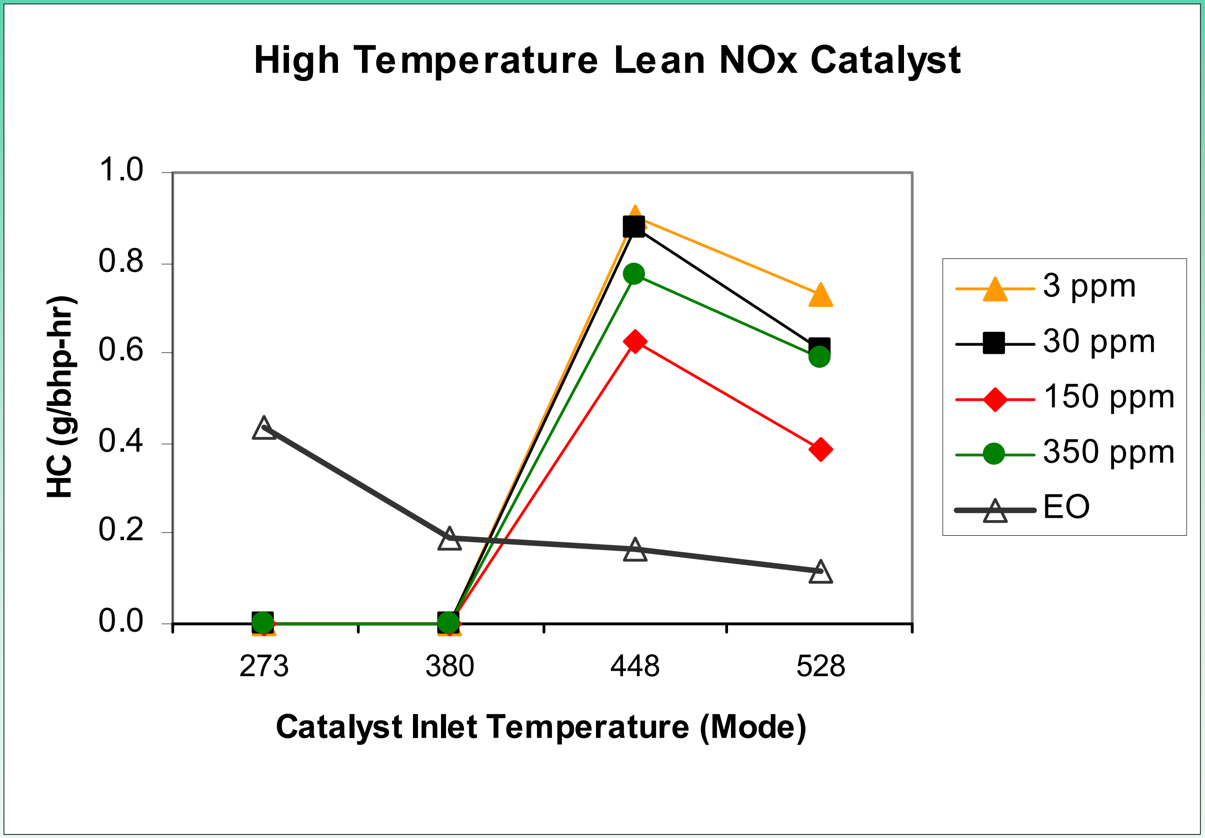
HC Slippage with HT Catalyst



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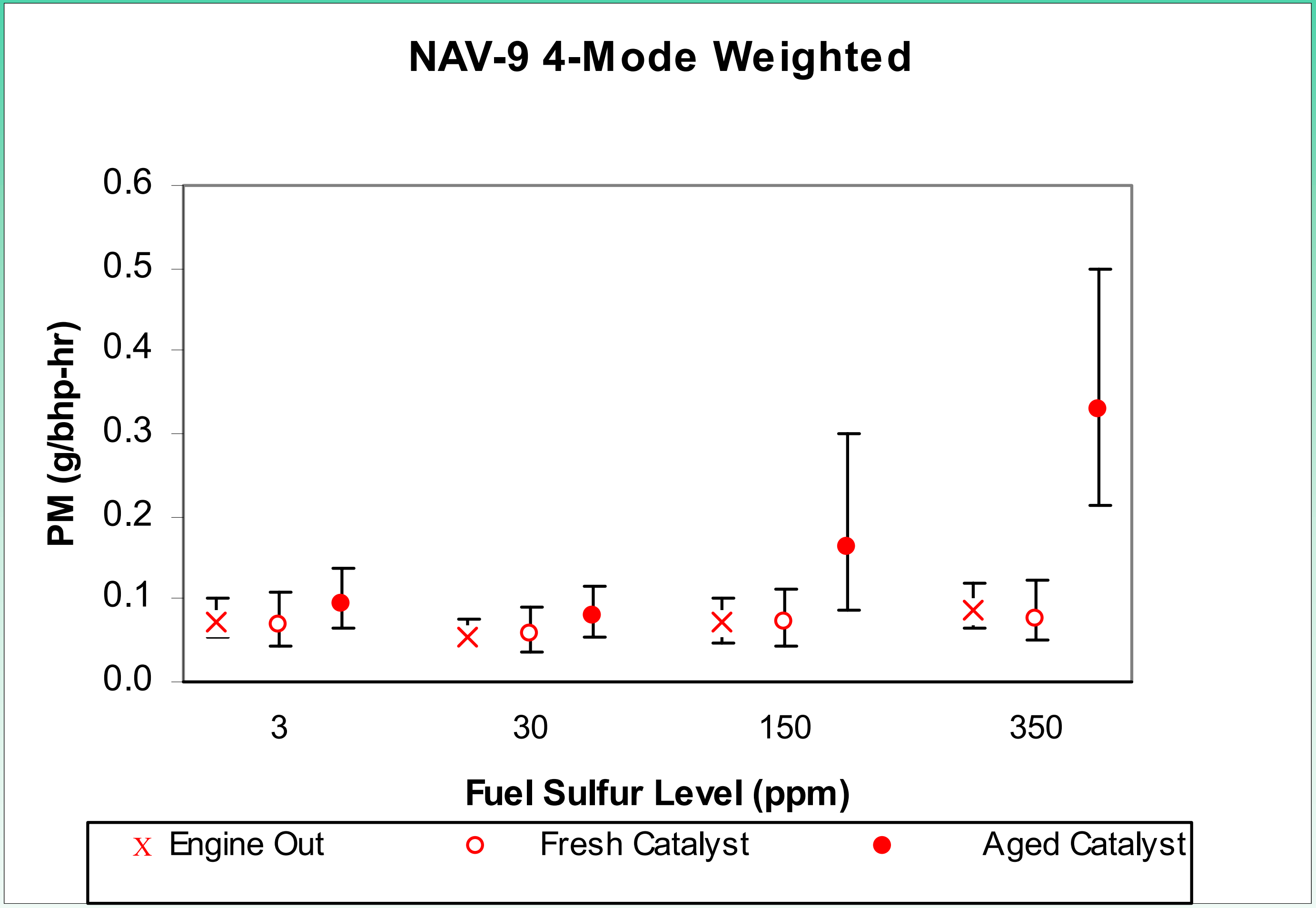
PM (SO_4) Increases with Catalyst Age



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Advance Petroleum-Based Fuels – Diesel Emissions Control (APBF-DEC) Program Overview

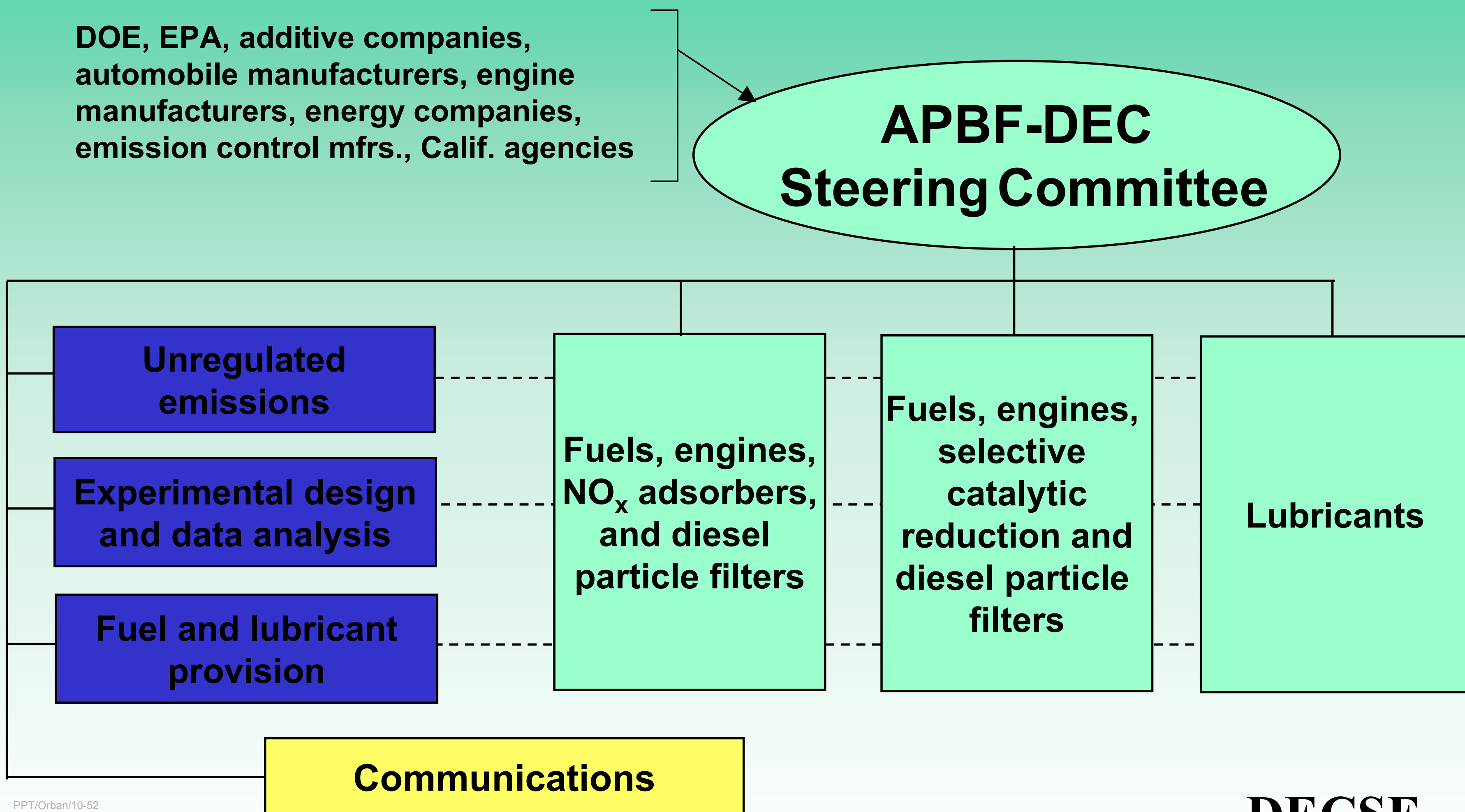
- Mission
- Organization/Summary
- Project Schedules

DECSE

APBF-DEC Mission

- Identify optimal combinations of fuels, lubricants, diesel engines, and emission control systems to:
  - Meet projected emission standards during the period 2000 to 2010 while maintaining continuous improvement in engine efficiency and durability
  - Maintain customer satisfaction with vehicle performance
  - Provide the basis for economical transport of people and goods
  - Meet additional potential constraints (e.g., emissions of unregulated substances, including ultra-fine particulate matter and greenhouse gases)
- Explore the potential to achieve even lower emissions of criteria and unregulated pollutants beyond 2010

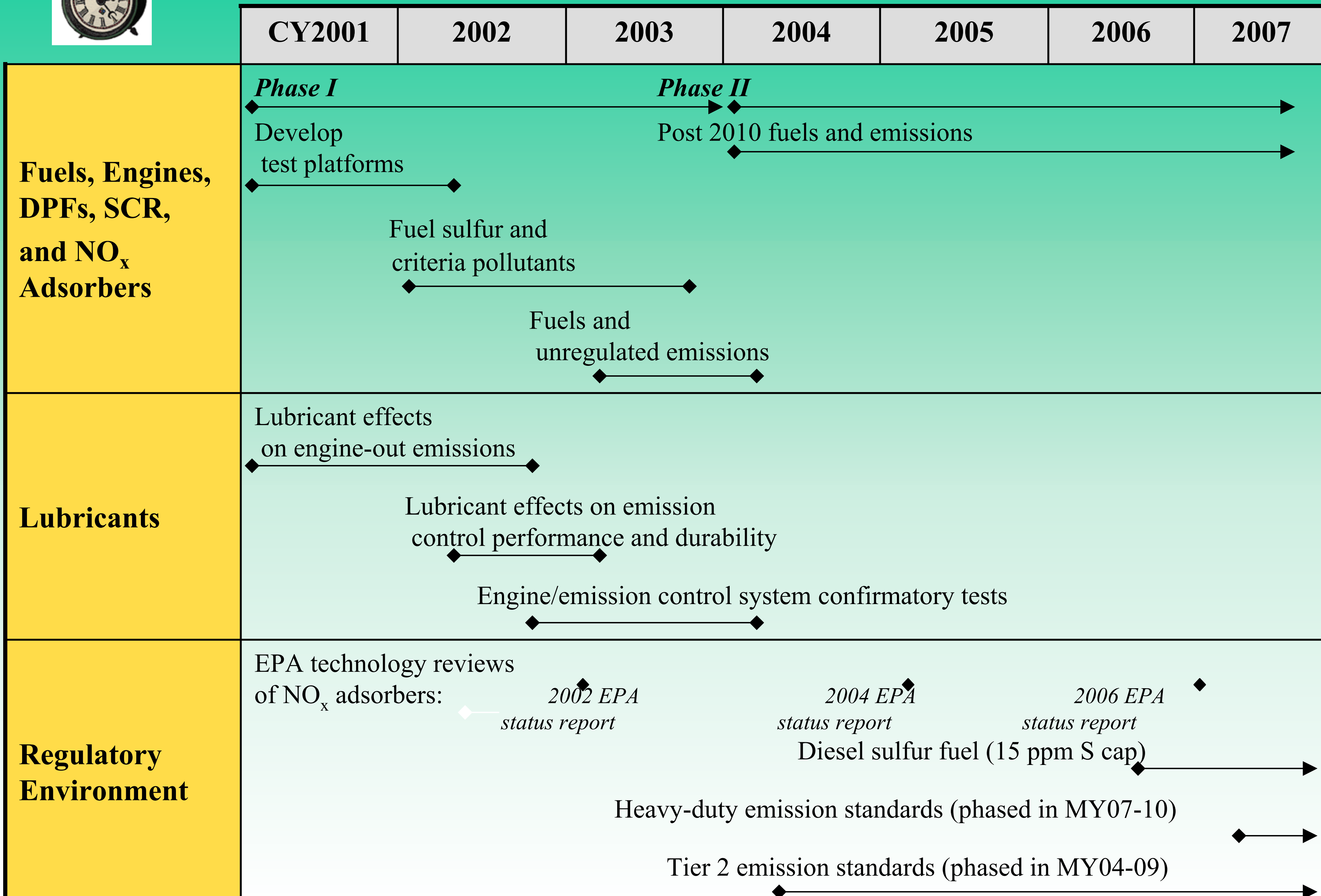
APBF-DEC Organization



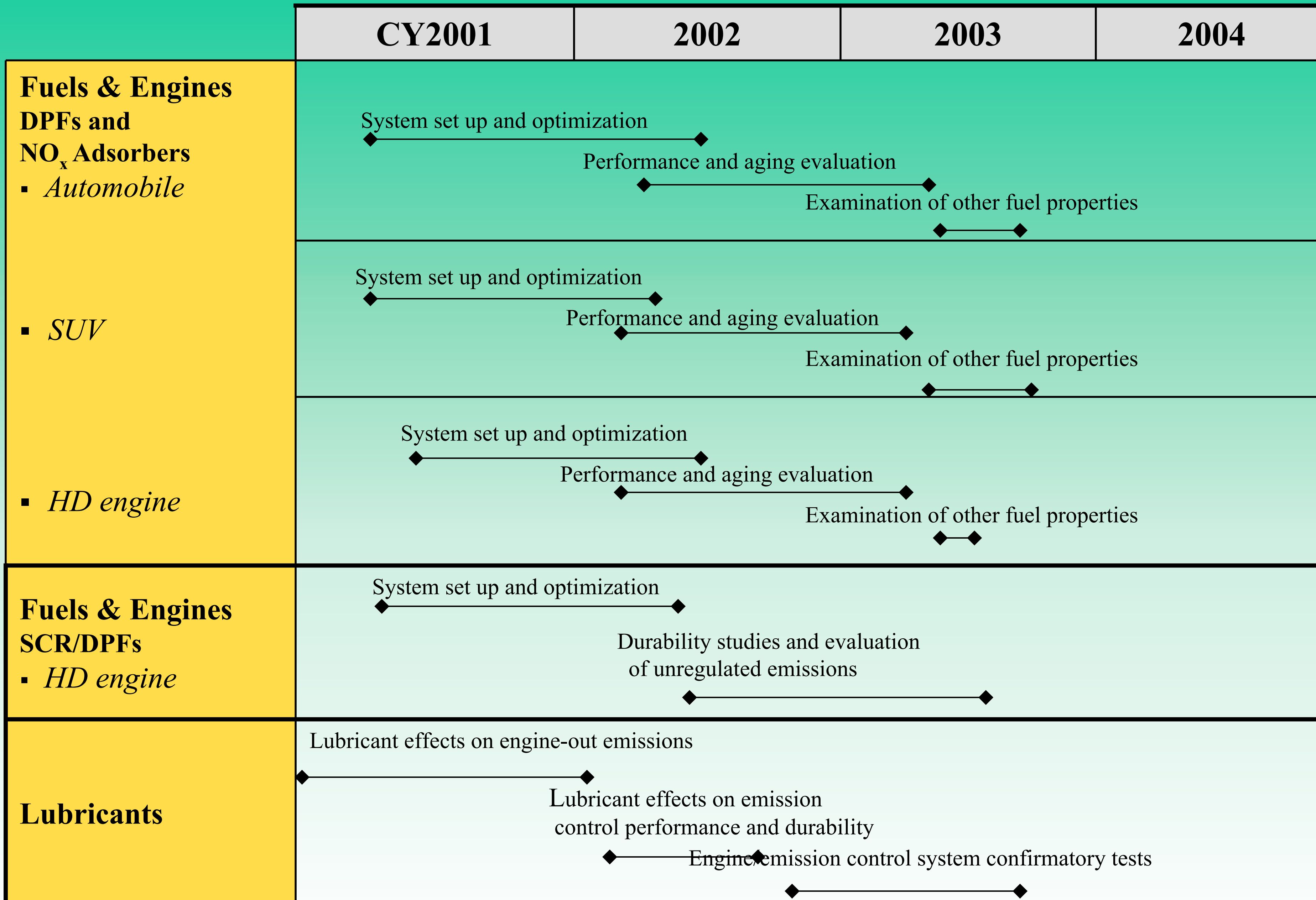
DEC Participants

- U.S. DOE
- U.S. Environmental Protection Agency
- American Petroleum Institute
- National Petrochemical and Refiners Association
- Engine Manufacturers Association
- Manufacturers of Emission Controls Association
- American Chemistry Council
- California Air Resources Board/South Coast Air Quality Management District

APBF-DEC Program Schedule



APBF-DEC Phase I Project Schedule



APBF-DEC Funding ($millions)

- Direct Needs - $22MM
  - DOE - 14.5
  - EMA - 2.4
  - API - 1.5
  - MECA - 1.95
  - ACC - 0.35
  - Calif. - 0.8
- Total Provided - 21.5

- In-Kind Needs - $14MM
  - DOE - 3.7
  - EMA - 4.7
  - API - 1.7
  - MECA - 3.1
  - ACC - 0.8
- Total Provided - 14