Final Update on APBF-DEC
EGR/DPF/SCR Demonstration Project
at SwRI

Chris Sharp, Magdi Khair - Southwest Research Institute
Ralph McGill – Sentech

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Objectives

- To Demonstrate The Low Emissions Performance of Advanced Diesels+Urea SCR+DPF (2 Different Systems)
- To Determine The Regulated And Unregulated Emissions W. &W/O Emission Controls
- To Examine The Emission Control System Durability over 6,000 hours
- To Sample Toxic Emissions For Analysis By Outside Lab
- To Evaluate Sensitivities of The Control System Performance To Fuel Variables

Emissions Goals: 2007 EPA HDE Standards
Participating Companies/Organizations

Automobile:
- DaimlerChrysler
- Ford
- GM
- Toyota

Engines:
- Caterpillar
- Cummins
- Detroit Diesel
- EMA
- International Truck & Engine
- John Deere
- Mack Trucks

Government:
- CARB/SCAQMD
- DOE
- EPA
- NREL
- ORNL

Emission Control:
- Argillon
- ArvinMeritor
- Benteler
- Clean Diesel Tech.
- Corning
- Delphi
- Donaldson Co.
- Engelhard
- Johnson Matthey
- MECA
- NGK
- Rhodia
- Robert Bosch Corp.
- STT Emtec AB
- Tenneco Automotive
- 3M
- Umicore

Energy/Additives:
- American Chemistry Council
- API
- BP
- Castrol
- Chevron Oronite
- ChevronTexaco
- Ciba
- Conoco-Phillips
- Crompton
- Ergon
- Ethyl
- ExxonMobil
- Infineum
- Lubrizol
- Marathon Ashland
- Motiva
- NPRA
- Pennzoil-Quaker State
- Shell Global Solutions
- Valvoline

Technology:
- Battelle
## Aftertreatment Systems - Systems A & B

<table>
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<tr>
<th>System</th>
<th>No. of Units</th>
<th>Volume, L</th>
<th>Syst. Vol./Eng. Displ.</th>
<th>Remarks</th>
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<tr>
<td>DPF</td>
<td>A: 2</td>
<td>B: 2</td>
<td>A: 45.6</td>
<td>B: 34.1</td>
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<td>SCR</td>
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<td>B: 4</td>
<td>A: 39.4</td>
<td>B: 31.0</td>
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<td>CUC</td>
<td>A: 1</td>
<td>B: 1</td>
<td>A: 8.5</td>
<td>B: 8.5</td>
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<tr>
<td></td>
<td>A: 1</td>
<td>B: 1</td>
<td>A: 93.5</td>
<td>B: 73.5</td>
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</table>
**Technical Approach -- Phase 2 (6000-hour Evaluation)**

- Aging performed in parallel on durability engines
- Emission tests every 2000 hours using performance engine
Effect of LPL-EGR* and DPF - DECSE 8ppm Fuel

Steady-State ESC Composite

- > 50% NOx Reduction with EGR
- HC, CO, PM nearly eliminated with catalyzed DPFs

Transient Composite

Low Pressure Loop EGR (includes DPF)
**Transient Emissions**--System A & B--DECSE 8 ppm Fuel - Composite

- Transient NO$_x$ stable for both systems
- Urea Injection problem on System A at 2000-hr point

**NO$_x$**

- Composite NO$_x$, g/hp-h
- Test Point: 200-hr, 2000-hr, 4000-hr, 6000-hr

**PM**

- Composite PM, g/hp-h
- Test Point: 200-hr, 2000-hr, 4000-hr, 6000-hr

*Pre-2007 Type PM Measurement System*
Steady-State Emissions--System A & B--DECSE 8 ppm Fuel – ESC
13-Mode Composite (Average 2 Cycles)

NO\textsubscript{x}

- System A NO\textsubscript{x} apparent degradation through 4000 hours, performance restored at 6000 hours
- System B NO\textsubscript{x} apparent degradation at 6000 hour point

Higher PM levels for ESC due to high temperatures at DPF inlet (sulfate production)

Pre-2007 Type PM Measurement System
**System A NO\textsubscript{x} Diagnostics - ESC, 6000-Hr Point**

- Gradual Loss of NO\textsubscript{x} Conversion with each test (similar behavior seen at 2000-hr and 4000-hr test points)
- Recovery of conversion following high-NO\textsubscript{x} burn-out
System A NO\textsubscript{x} Diagnostics- Conclusions

- SCR Catalyst deactivation was real (though apparently reversible) and present on both legs equally at 2000-Hr and 4000-Hr points.
- Catalyst deactivation was reversed at start of 6000-Hr point.
- During test episodes, progressive loss of conversion from test to test observed following initial stable period.
  - Overall NH\textsubscript{3}-to-NO\textsubscript{x} ratio is ~ 1.02 for ESC calibration.
- Deactivation reversed at high temperature (> 400 C) with excess NO\textsubscript{x} (NH\textsubscript{3}:NO\textsubscript{x} < 0.5).
  - Recovery during 4000-6000 durability during a period of high engine-out NO\textsubscript{x} following an EGR cooler problem (*major hint*).
  - Recovery during deliberate experiment at 6000-Hr point.
- Temporary deactivation of SCR catalyst during periods of excess NH\textsubscript{3} dosing*
- No apparent thermal degradation of SCR catalysts after 6000 Hours.

* Matches with contents of invited talk by Oliver Kroecher, Paul Scherrer Institute, CLEERS Symposium, Dearborn, MI, May 2005.
System B Backpressure - Durability Engine, ESC Mode 10

0 - 2000 Hours

2000 - 4000 Hours

4000 - 6000 Hours

Loss of Passive Regeneration on Left-Side DPF
System B NO\textsubscript{x} Diagnostics - Conclusions

- Left-side DPF appears to have lost passive regeneration during aging
- Increased backpressure on left-side branch caused flow imbalance with more exhaust on right side
  - Right side $\rightarrow$ Not enough ammonia $\rightarrow$ lower conversion
  - Left side $\rightarrow$ Too much ammonia $\rightarrow$ Ammonia slip (to NO\textsubscript{x} in CUC\textsuperscript{*})
  - Dual legs are a problem again
- Increased engine backpressure resulted in higher catalyst temperatures
  - SCR temperatures in Modes 3-7 up from 490 C to 520 C
  - Lower NO\textsubscript{x} conversion due to higher temperatures (no effect on transient)
- Loss of conversion related to DPF problem
- No apparent thermal degradation of SCR catalysts after 6000 hours

\textsuperscript{*} CUC = Clean-up Catalyst
Nitrous oxide—Steady-State & Transient —At the 6000-hour Point

Tailpipe N$_2$O levels are roughly 10% of tailpipe NO$_x$ level.
**Ammonia Slip -- Steady-State & Transient -- At the 6000-hour Point**

**NH₃ levels are roughly equivalent to DPF-out particulate levels**
Transient BSFC increase of roughly 1-2% vs Base Engine

ESC BSFC increase of roughly 4-5% vs Base Engine
  Most, if not all of the increase is due to EGR+DPF

Urea Consumption as percentage of fuel consumption
  System A ~ 1.8% transient and ~ 3.8% ESC (all +/- 0.2%)
  System B ~ 1.4% transient and ~ 3.2% ESC (all +/- 0.2%)

* Base Engine NOx = 3.5 g/hp-hr
Program is Complete

Both Systems have completed the 6000-hour performance evaluation

Systems A and B are showing some performance differences mostly based on their size relative to that of the engine displacement.

After 6000 hours SCR catalyst performance appears to be holding in general.
  - Short-term, reversible deactivation of System A catalysts observed

After 6000 hours DPF performance is still good.
  - Problem with passive regeneration on one of System B DPFs

It appears that this combination of technologies has the potential to meet the 2010 emissions limits

Closed Loop Controls are essential to maintain 2010 emission levels