Urea SCR and DPF System for Diesel Sport Utility Vehicle Meeting Tier 2 Bin 5

DOE and Ford Motor Company Advanced CIDI Emission Control System Development Program
(DE-FC26-01NT41103)

Diesel Engine Emission Reduction Conference

September 2, 2004

Presentation Overview

- Program Overview
- Results with Fresh Catalyst System
- System Durability
- Exhaust Gas Sensor Development
- Urea Infrastructure Study
- Phase III
- Conclusions

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Program Overview

DOE Ultra-Clean Fuels Program

Outline of Ford's program to achieve Tier 2 FTP emission standards for 2007 using low sulfur diesel fuel as an enabler for a high efficiency aftertreatment system.

Primary Contractor

Ford Research and Advanced Engineering

Subcontractors

ExxonMobil Research and Engineering

FEV

Catalyst Suppliers

ENGELHARD

JM Johnson Matthey

umicore

Phase I - Initial build/test phase (July 01-July 02)
Establish baseline emission control system
Deliver engine dynamometer NOx and PM test results
Deliver prototype vehicle NOx and PM test results
Deliver urea delivery (infrastructure) prototype

Phase II - System/component optimization phase (July 02-July 04)
Define final system hardware components
Deliver NOx and PM performance data from fresh system

Phase III - Durability phase (July 04-July 05)
Definition of durability test procedure
Final NOx and PM emission levels
Final report for the completed program

FEV Program

Concept Design

- CFD Modeling including urea injection

Engine Dynamometer

- Baseline and rapid warm-up testing
- Urea SCR/CDPF optimization
- Transient FTP testing

Emission Control System Durability

- 120K miles on engine dyno

ExxonMobil Program

SCR Catalyst Development

- Durable, high NOx conversion from 150° to 600°C with low N_2O make

Urea Infrastructure

- Co-fueling concept
- Cold-climate urea usage
- Infrastructure studies

Fuel Development

- Make and use fuel, which will be typical of 2007 production with 15 ppm sulfur cap

Diesel Fuel Properties

- ExxonMobil blended 14,000 gallon batch to represent typical 2007 ULSD

Fuel Property	Est. Avg. '06 Diesel Properties	Proposed DOE Program Min/Max	Program Fuel Delivered	Proposed 2007 Cert. Fuel
Sulfur, ppm	15*	10 / 15	**12.5**	7 / 15
Density, kg/m³	850	820 / 850	**841.1**	839 / 865
Aromatics, vol. %	32	25 / 32	**29.5**	27 min
Polyaromatics, wt. %	10	6 / 11	**11.0**	no spec
Cetane number	46	44 / 48	**44.9**	40 / 50
T50, C	267	250 / 280	**249**	243 / 282
T90, C	306	300 / 320	**307**	293 / 332

* As delivered to the vehicle

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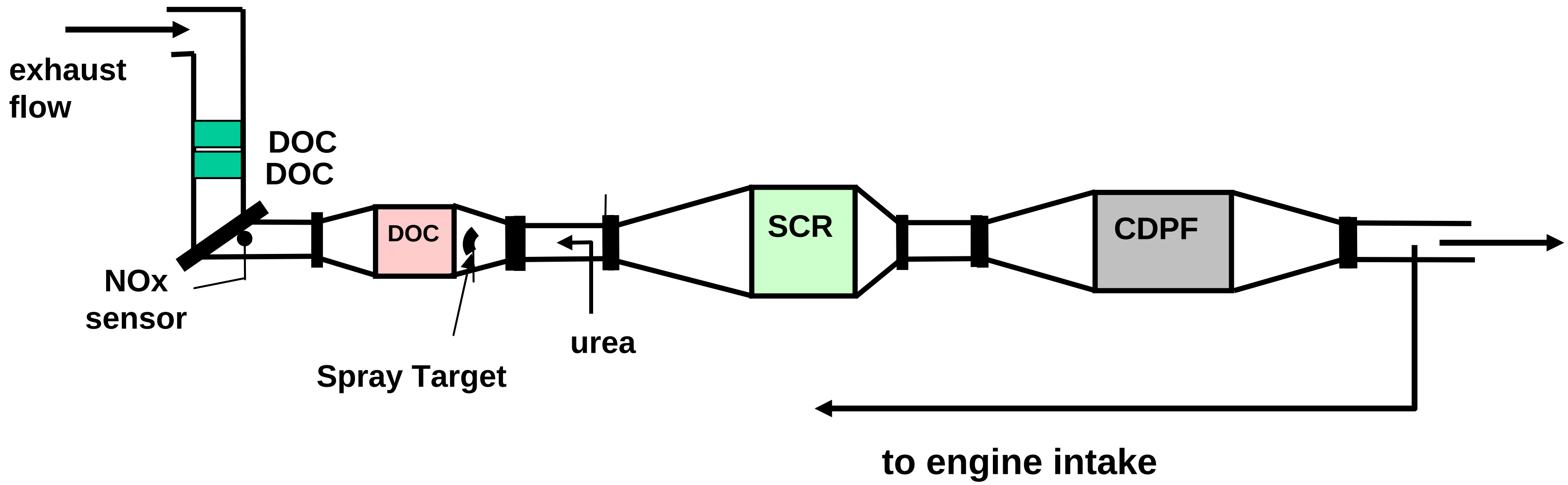
Results with Fresh Catalysts

LDT Exhaust System

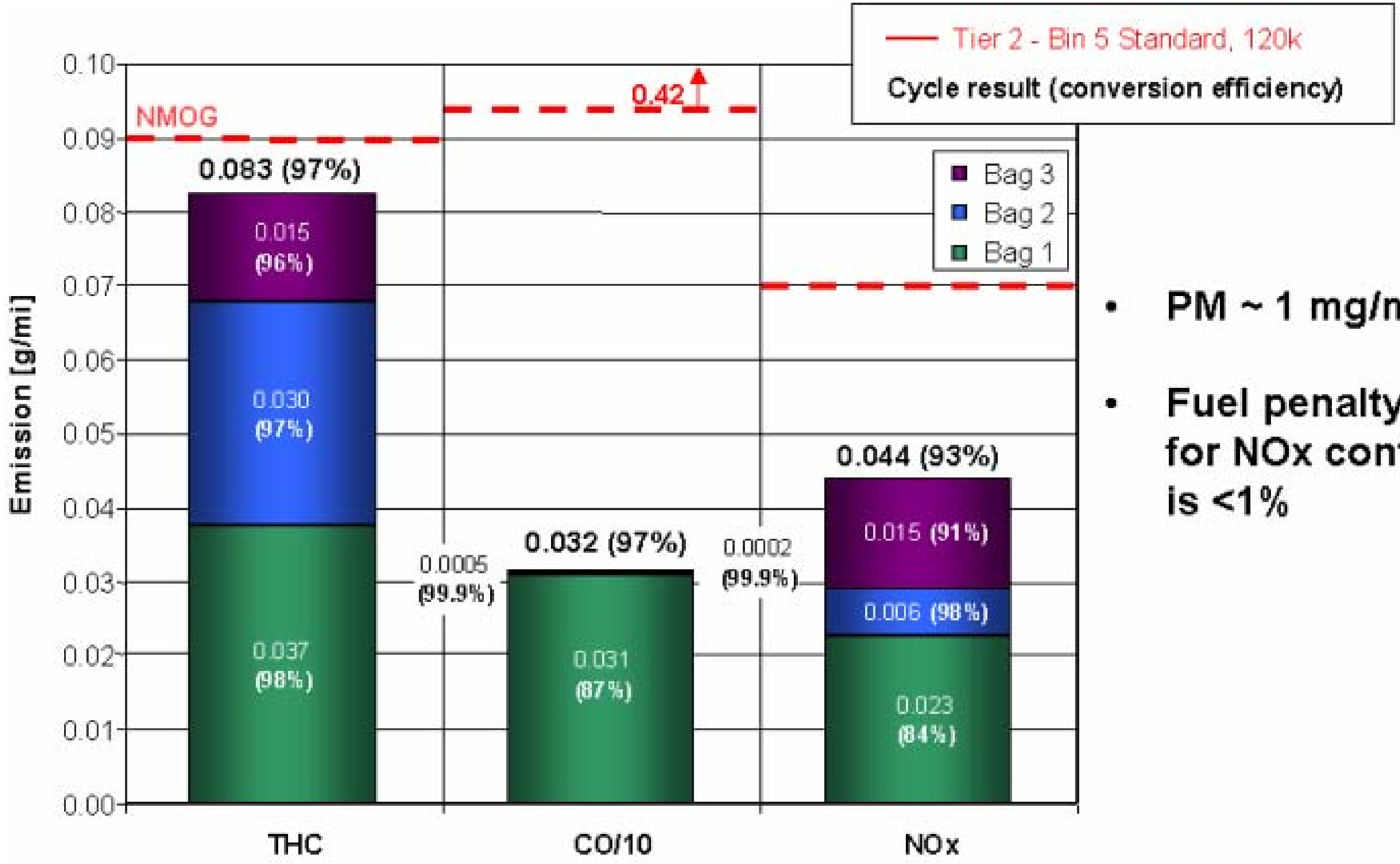
>90% FTP NOx conversion, 0.05 g/mi TP NOx



- Engine-out NOx lowered by 40% with increased EGR
- Low tailpipe NOx achieved with rapid warm-up strategy
  - lower thermal mass upstream of catalyst system
  - engine calibration changes during cold start (post injection & inc. idle speed)

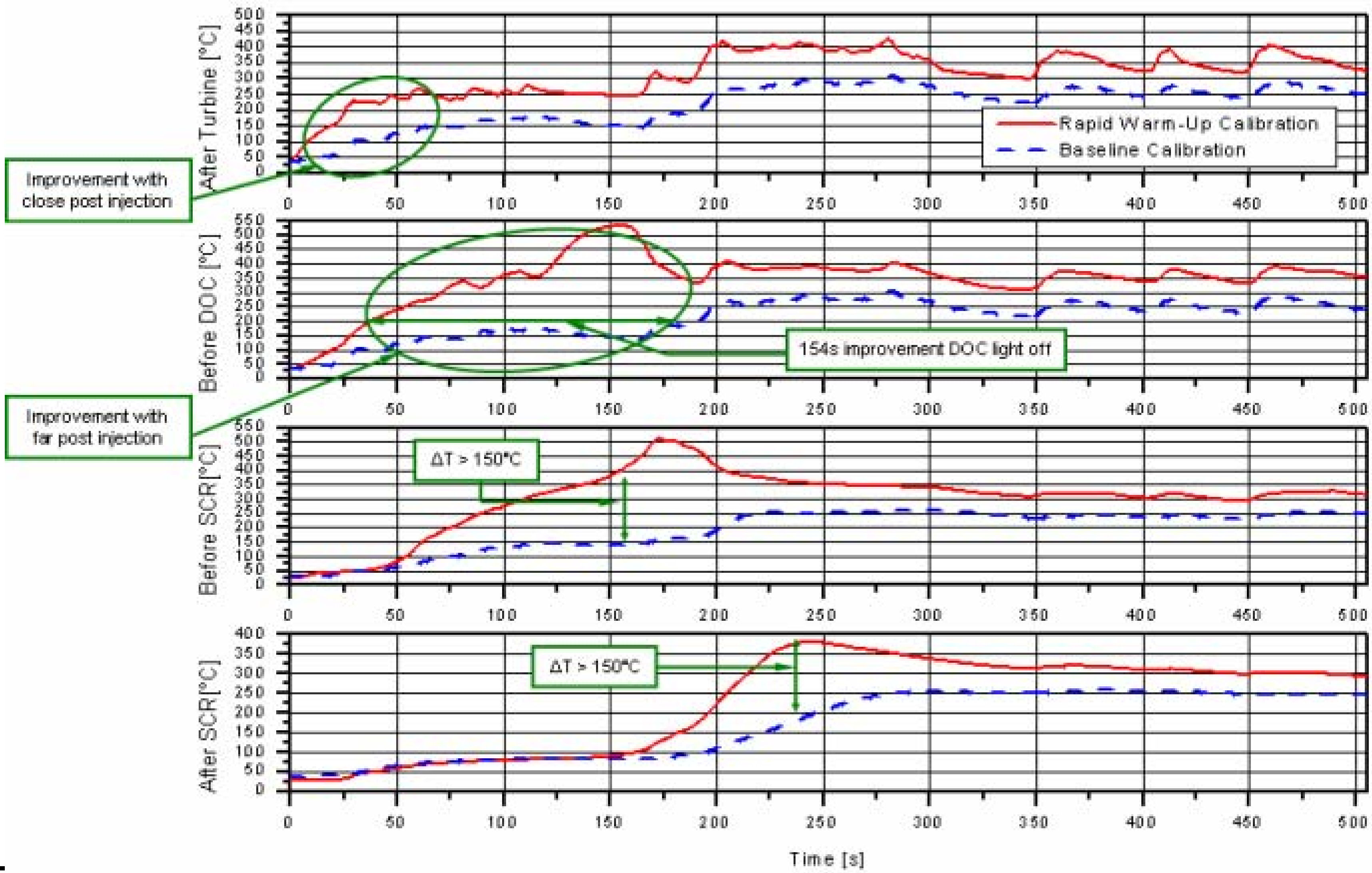
FTP-75 Tailpipe Emissions and Conversions

(with fresh catalysts on engine dyno)

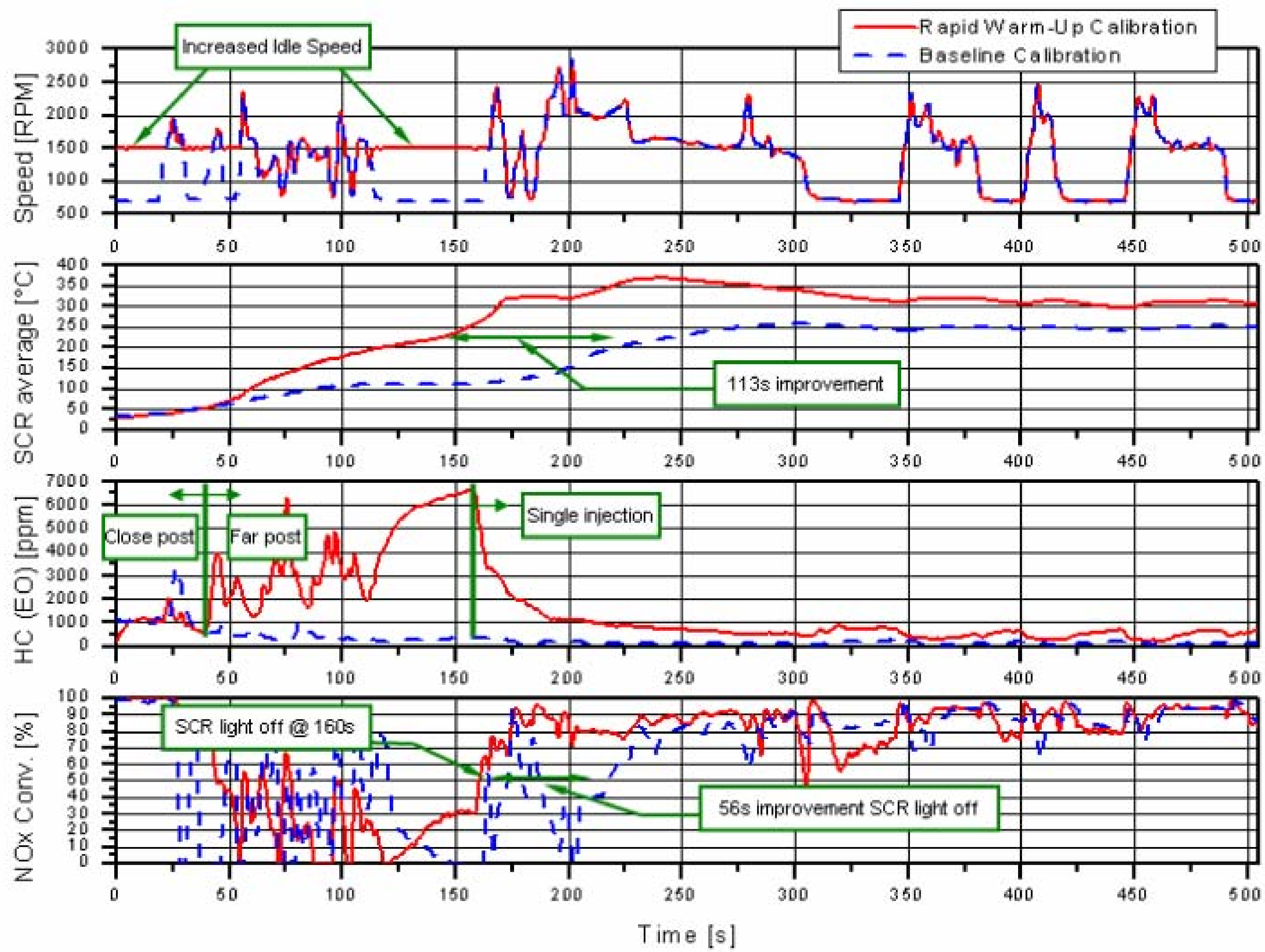


- PM ~ 1 mg/mi
- Fuel penalty for NOx control is <1%

Rapid Warm-up - *Improvement*



Rapid Warm-up - *Improvement*



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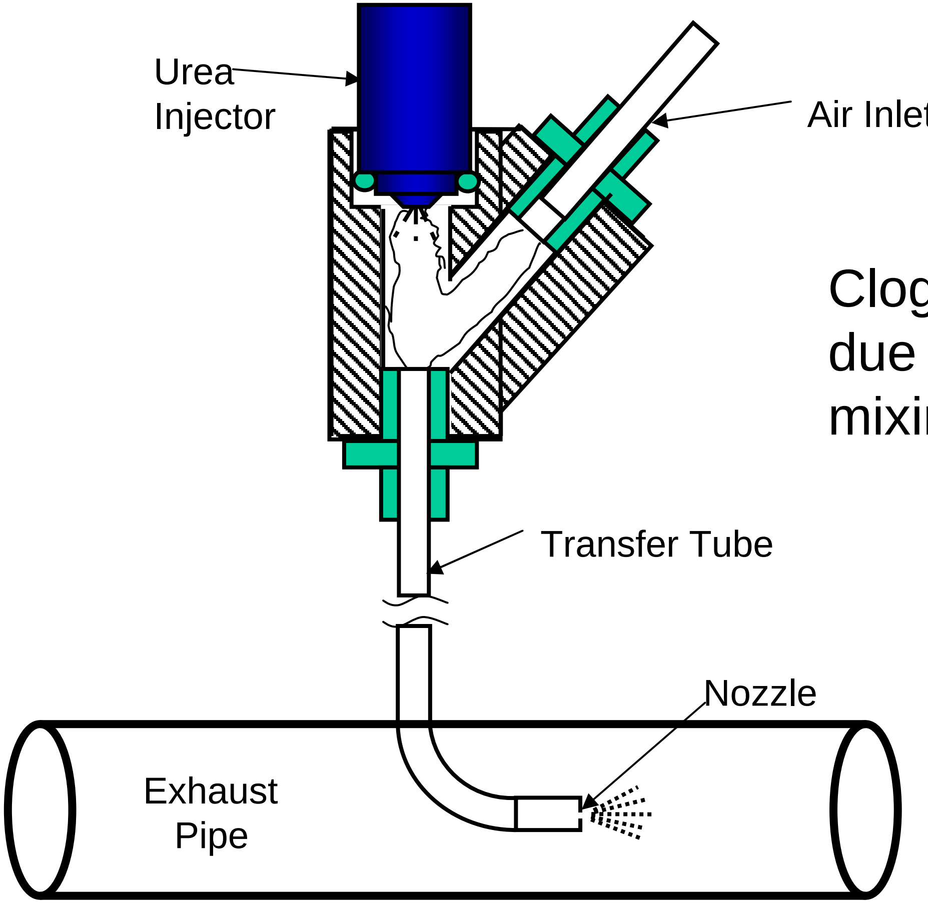
System Durability

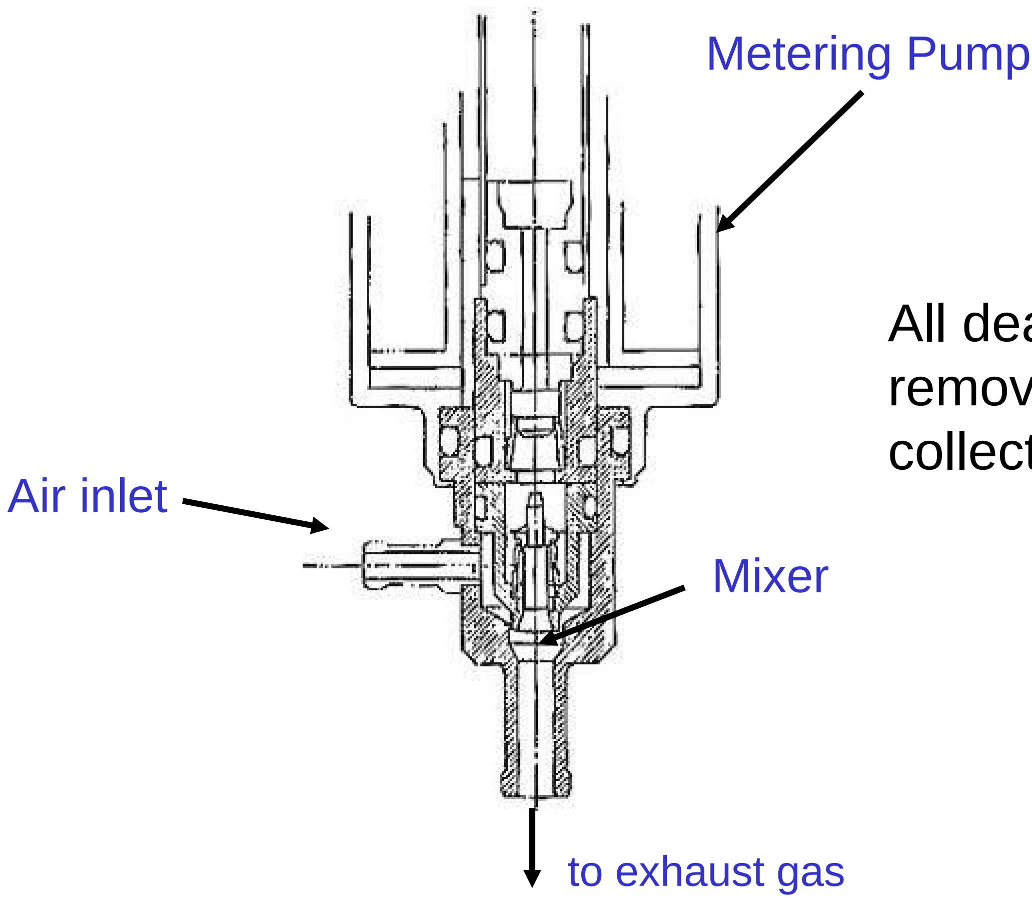
Urea Dosing System: Previous Urea Injection System



Clogging may occur due to urea collection in mixing chamber.

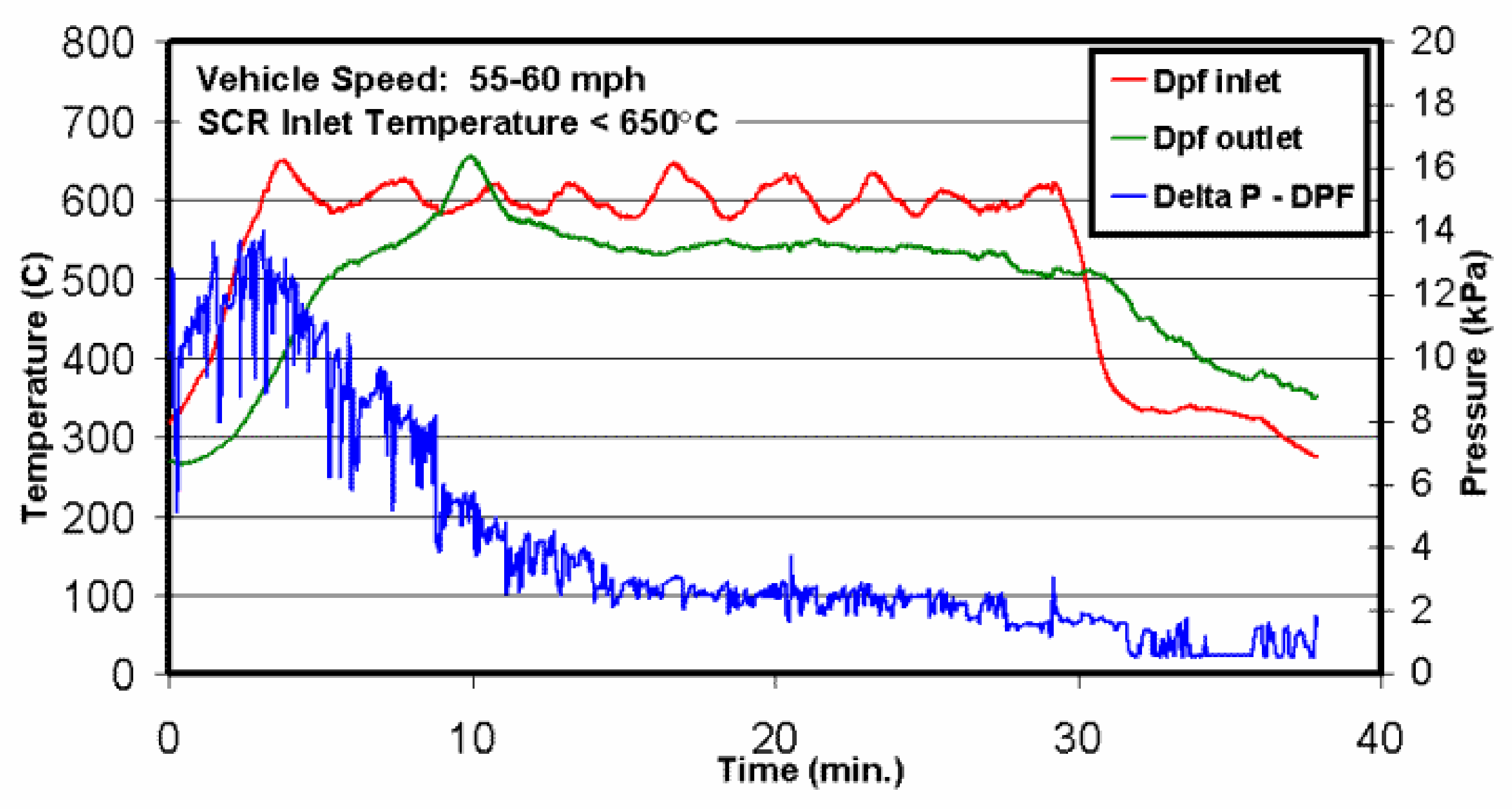
Improved Urea Dosing System

With Integrated Metering Pump/Mixer



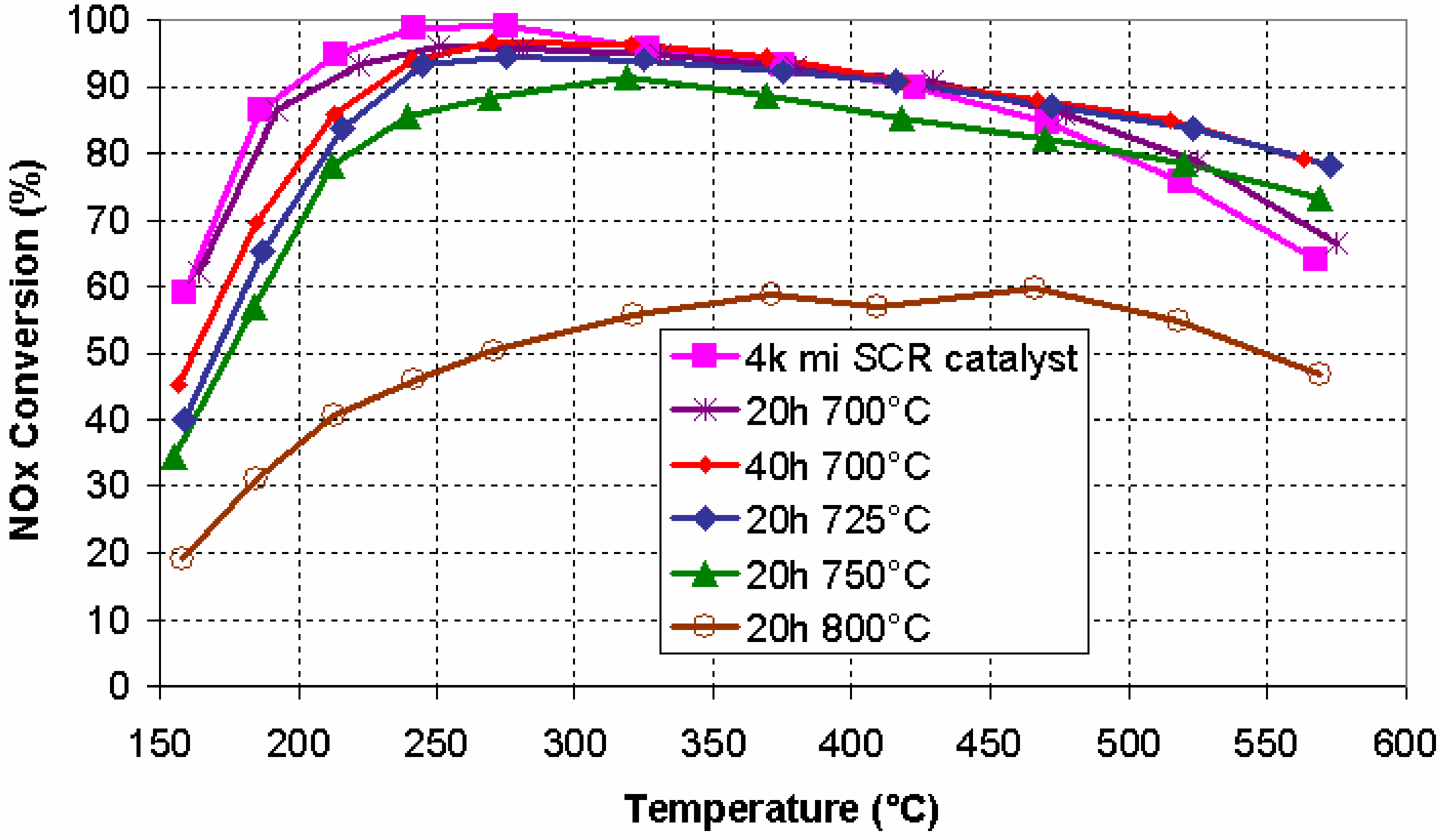
All dead volume has been removed to avoid urea collection and clogging.

SCR Catalyst Durability: LDT CDPF Regeneration



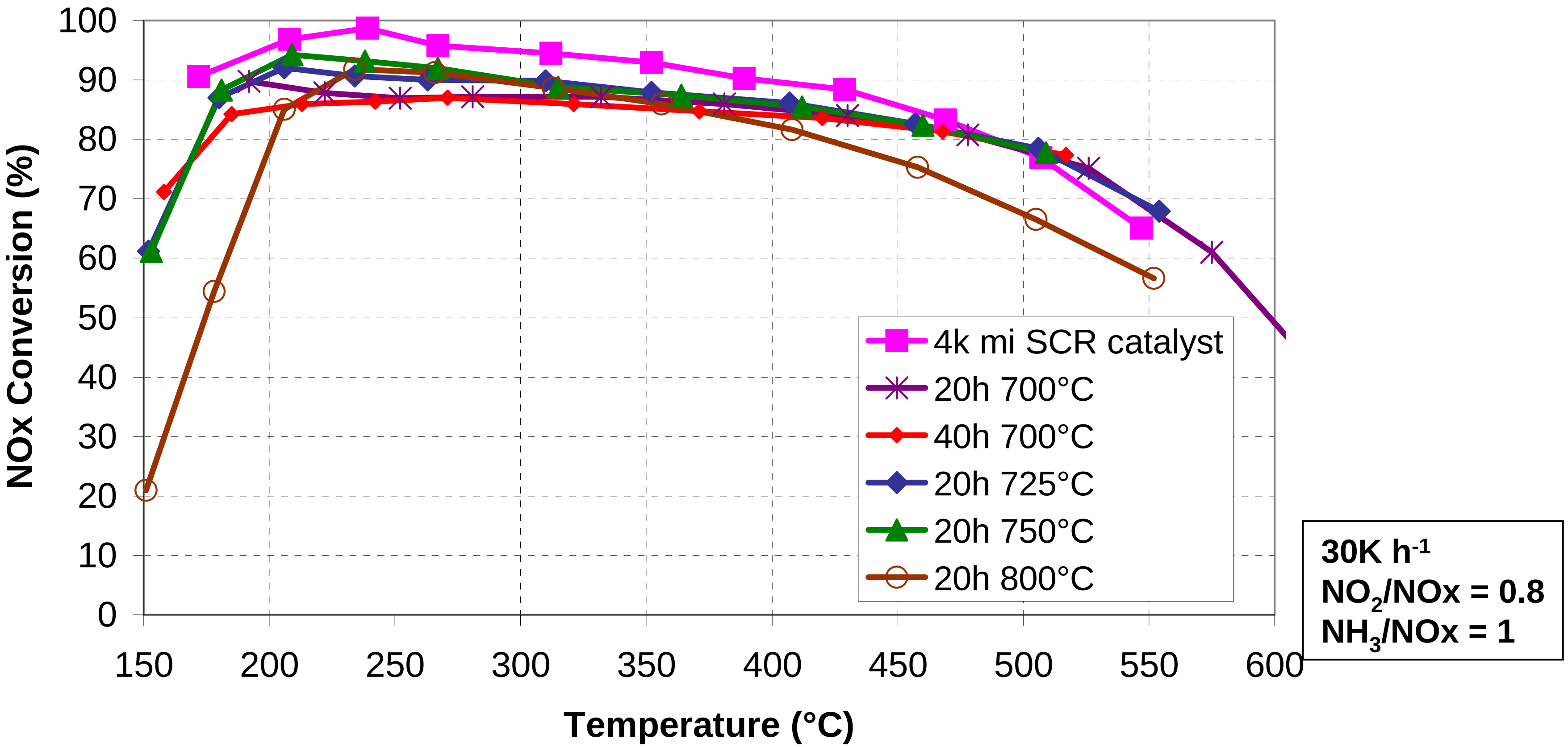
- SCR activity was identical before and after regeneration

SCR Catalyst Durability: High Temperature



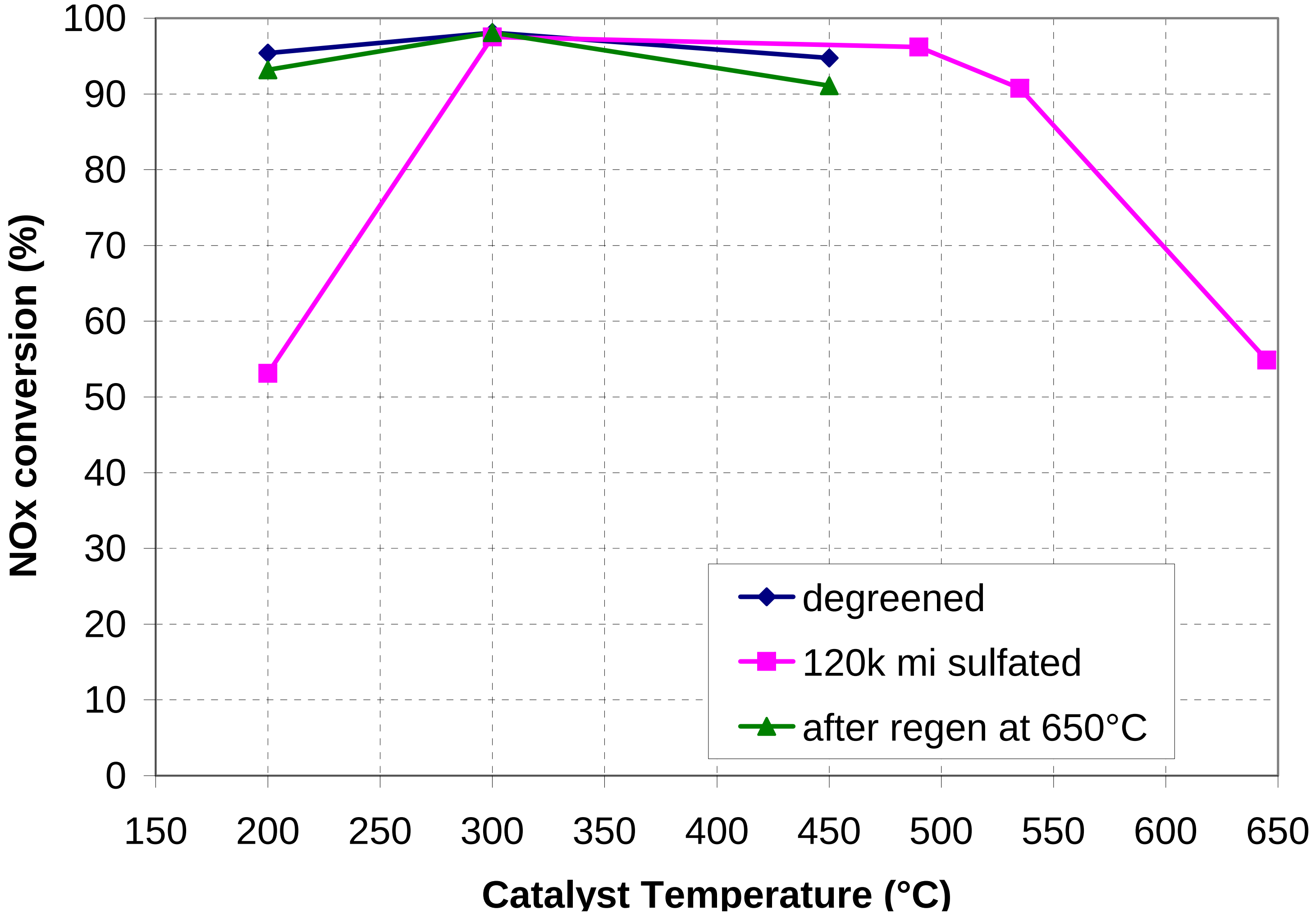
- With 20% NO_2/NOx feed, the catalyst is durable to 750°C

SCR Catalyst Durability: High Temperature



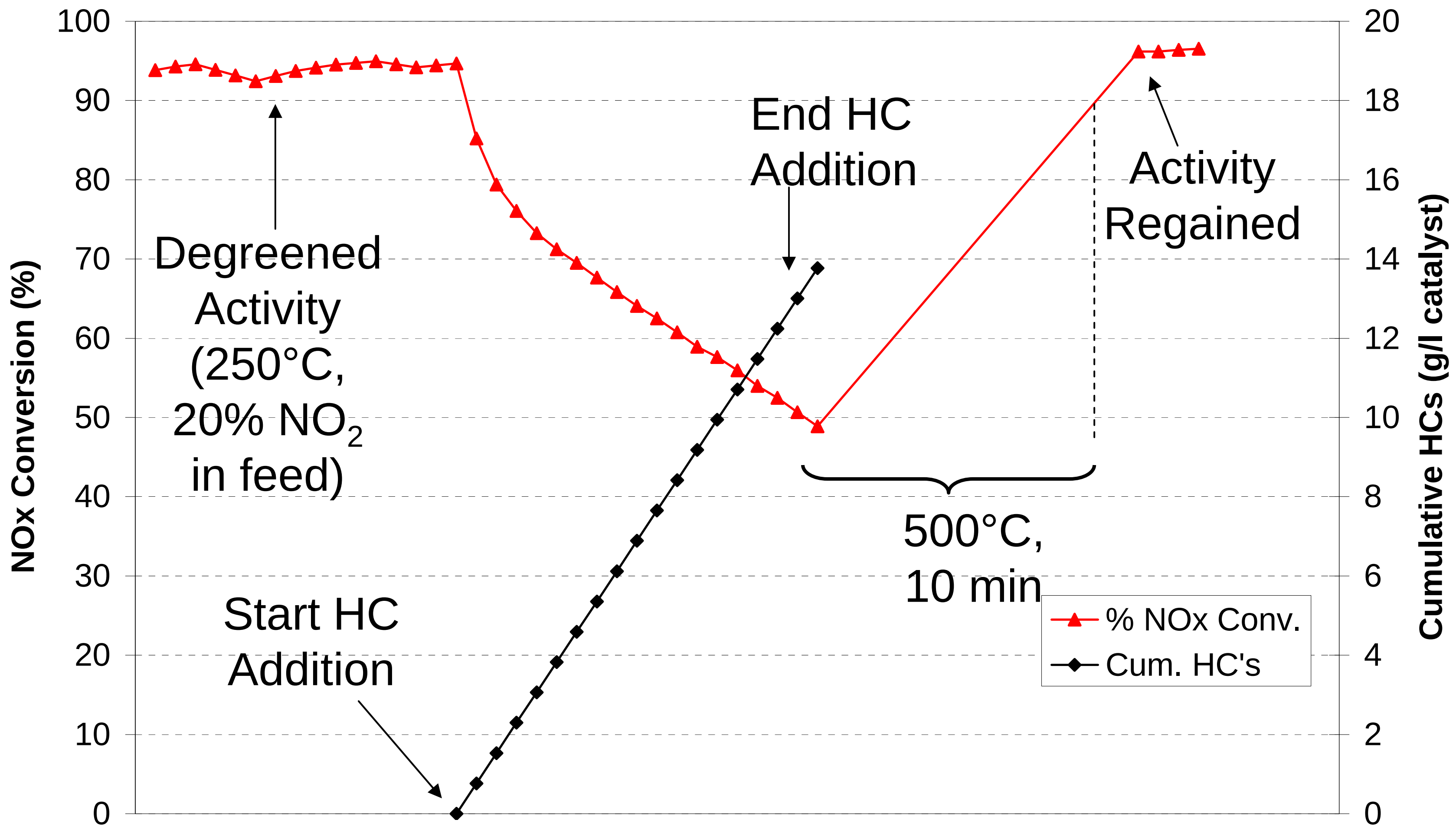
- With 80% NO_2/NOx feed, the catalyst is durable to 800°C

SCR Catalyst Durability: Sulfur



- Sulfur poisoning is reversible after 650°C, lean

SCR Catalyst Durability: HC



- HC poisoning is reversible after 500°C, lean

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Exhaust Gas Sensor Development

Emission Sensors

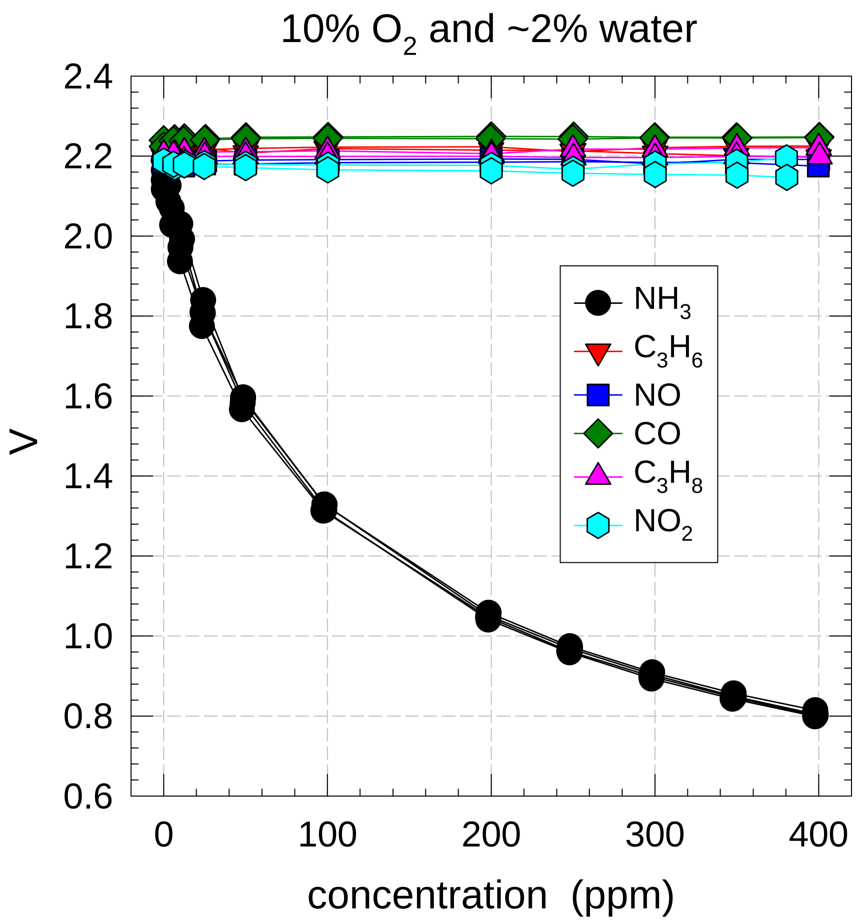
NOx:

- Sensors used in monitoring both engine out and tailpipe NOx levels
- Pre-production prototypes developed by a supplier with no major issues
- Production-intent sensors to be used for durability studies

NH_3:

- Used in monitoring NH_3 slip
- Prototypes under development by a supplier
- To be included in durability studies

Laboratory Data for Prototype NH_3 Sensor



- Good NH_3 sensitivity with little direct sensitivity to interfering gases such as CO, HC, NOx and O_2
- Some sensitivity to H_2O

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Urea Infrastructure Study

Co-fueling Hardware Status

- Co-fueling hardware completed
  - Co-axial nozzle with fill-neck insert provided by a major nozzle manufacturer
  - Urea pumping system with flow meter
  - Urea tank integral with dispenser
  - Urea heating system
  - 32.5 wt% urea in water assumed

Co-fueling Demonstration

Plan:

- Evaluate durability and reliability of a co-fueling system
- Use F350 truck fitted with urea tank and modified filler neck
- Drain fuel and urea tanks as necessary for subsequent refilling
- Inspect fuel and urea samples for cross-contamination
- Inspect interface parts for wear/damage

Results:

- Urea flow measurement and shutoff operated as intended
- Nozzle/insert seal showed intermittent leak of ~0.5% urea to fuel

Next Steps:

- Supplier is improving nozzle and will supply test unit

Low Temperature Capability

Results

- No suitable cold-temp additives identified
- Cold room testing indicated heating system prevented freeze-up and allowed urea refueling down to –20°F
- Power measured at 0°F and –20°F
- Cost: $4/day and $6/day ($0.11/kW-hr)

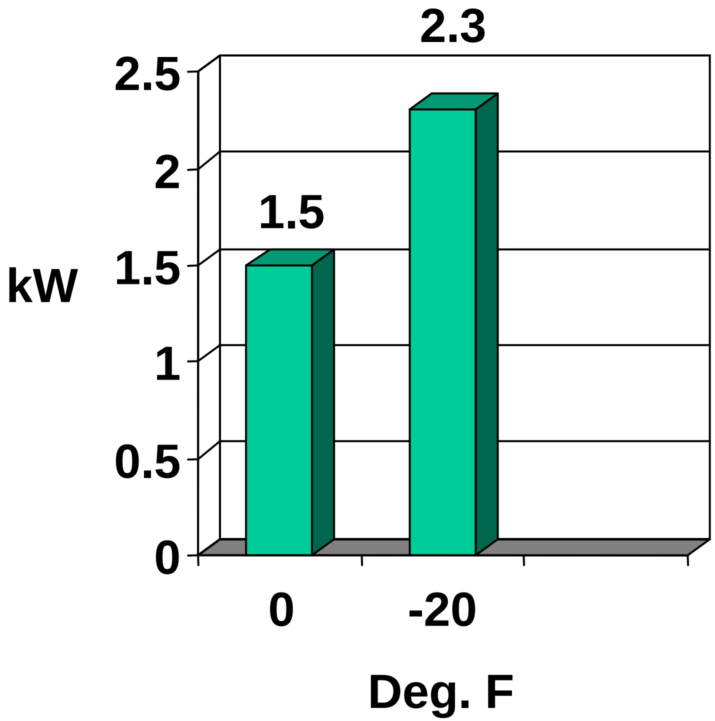
Recommendations

- Heater system is feasible
- Three heater system approach is anticipated for urea heating in US:
  - no heaters for temperatures > 12°F
  - line heaters only for temperatures > 5°F
  - full heaters for temperatures to –20°F

Issues

- Concerns over power outage and system malfunction

Power Consumption



Urea Infrastructure Economics

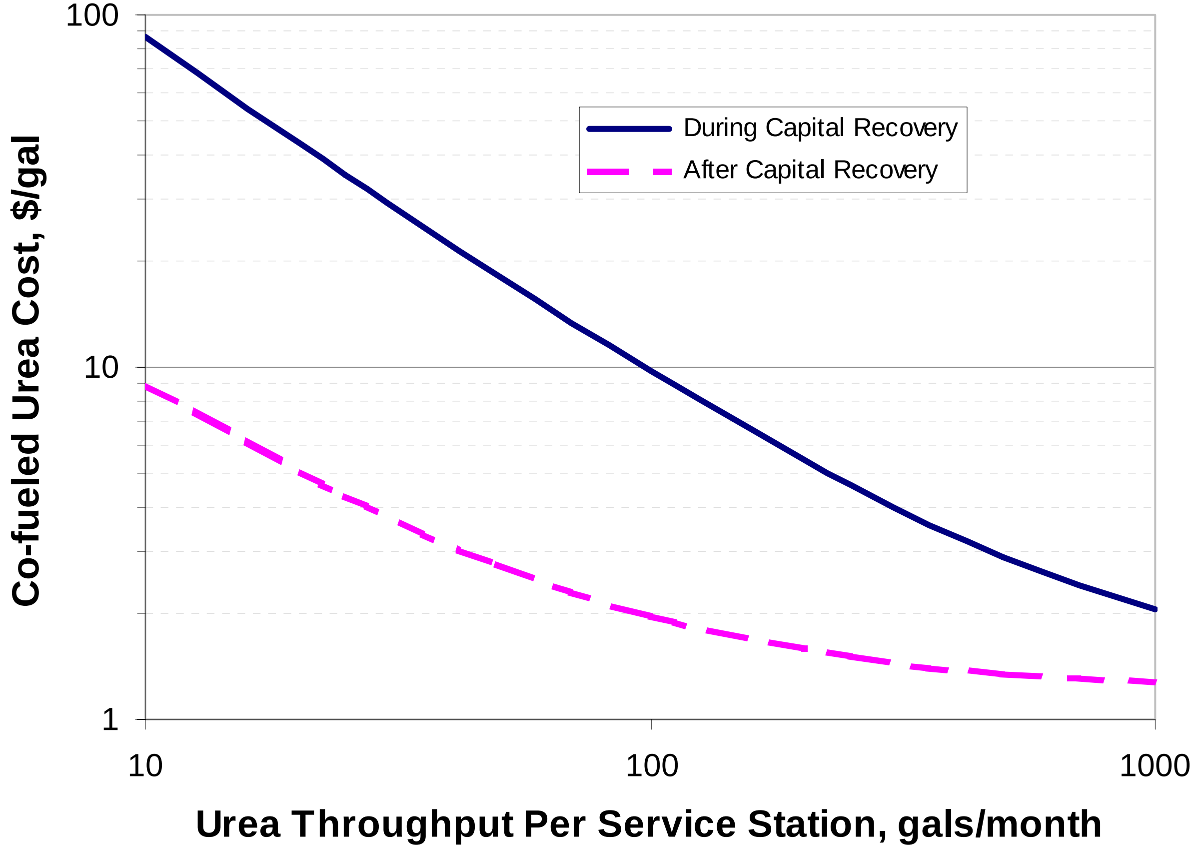
Background:

- A study was conducted to evaluate the costs of delivering aqueous urea to SCR vehicles at the service station.

Assumptions:

- Vehicle fuel consumption, population and growth from DOE Energy Information Administration's 2003 Annual Energy Outlook (AEO)
- Vehicle distribution & mileage accumulation by vehicle age using EPA MOBILE6
- Urea use is 2% of vehicle diesel consumption
- ROCE of 15% for service station investment, with a 3 year capital recovery period
- Projected urea costs are dependent on new heavy duty vehicles using urea beginning in 2007

Co-fueled Urea Cost vs. Demand



Urea Infrastructure Economics – Study Findings

- ***Scenario 1: Introduction of Co-fueled Urea in 2007***
  - Est. cost during capital payout period (2007-2010) is $42/gal.
  - In 2010, urea cost is expected to drop to approximately $3.76/gal.
  - Long-term cost is estimated to be $2/gal, due to projected increase in urea SCR vehicles
- ***Scenario 2: Introduction of Bottled Urea in 2007 and Co-fueled Urea in 2010***
  - Est. cost of bottled urea to the retail location is $3.66/gal.
  - Est. cost of co-fueled urea introduced in 2010 is $18/gal.
  - Co-fueled urea could cost the same as bottled urea if LDD vehicle volume is much higher than expected (8% of total LD volume vs <1%).
- ***Scenario 3: Introduction of Bottled Urea in 2007 and Co-Fueled Urea Phase-in Starting 2010***
  - Introduce co-fueling at only the highest throughput stations (<1% of stations).
  - Long-term co-fueled urea cost estimated to be $1.50/gal.
  - The switch from bottled urea to co-fueling would depend on the economics of individual service stations.

Urea Infrastructure Economics – Conclusions

- The cost to develop an infrastructure for delivery of aqueous urea to light-duty diesel vehicles is much less expensive using bottled urea, as wide-scale introduction of co-fueling is very costly.
- Co-fueling costs would be lowest if installations are phased-in gradually at the highest throughput stations, starting in 2010.
- The long-term price of co-fueled aqueous urea under such a scenario is expected to be $1.50 to $2 per gallon.

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Phase III

Phase III Timing Plan

Task 3.1 Urea Infrastructure Development (EM)

Task 3.2 Durability Testing

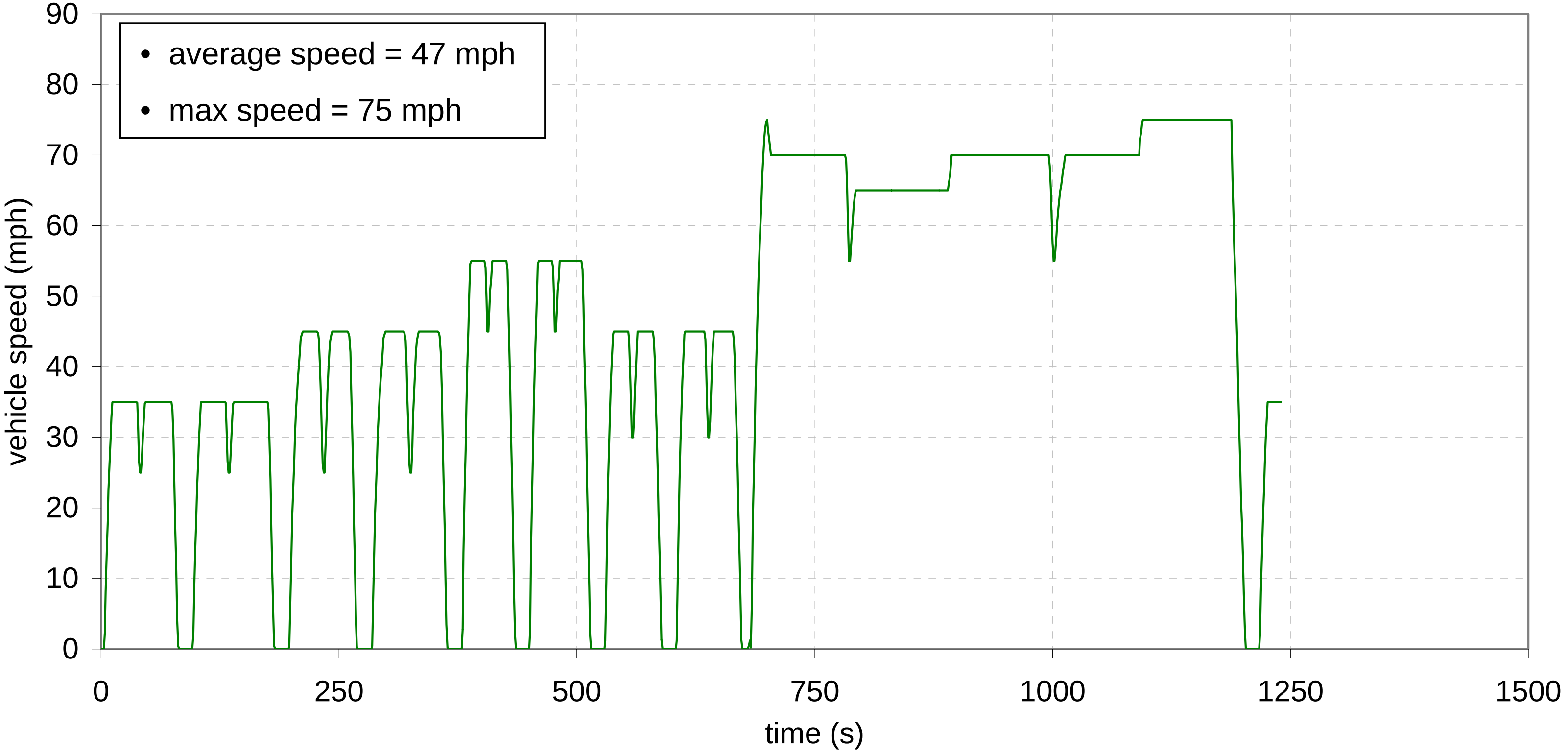
- 3.2.1 Durability Test Definition
- 3.2.2 Installation of Final ECS on Vehicle & Dyno
- 3.2.3 ECS Durability Testing
- 3.2.4 Catalyst and Control Support
- 3.2.5 Low Sulfur Fuel Support

Task 3.3 Post Durability Evaluation

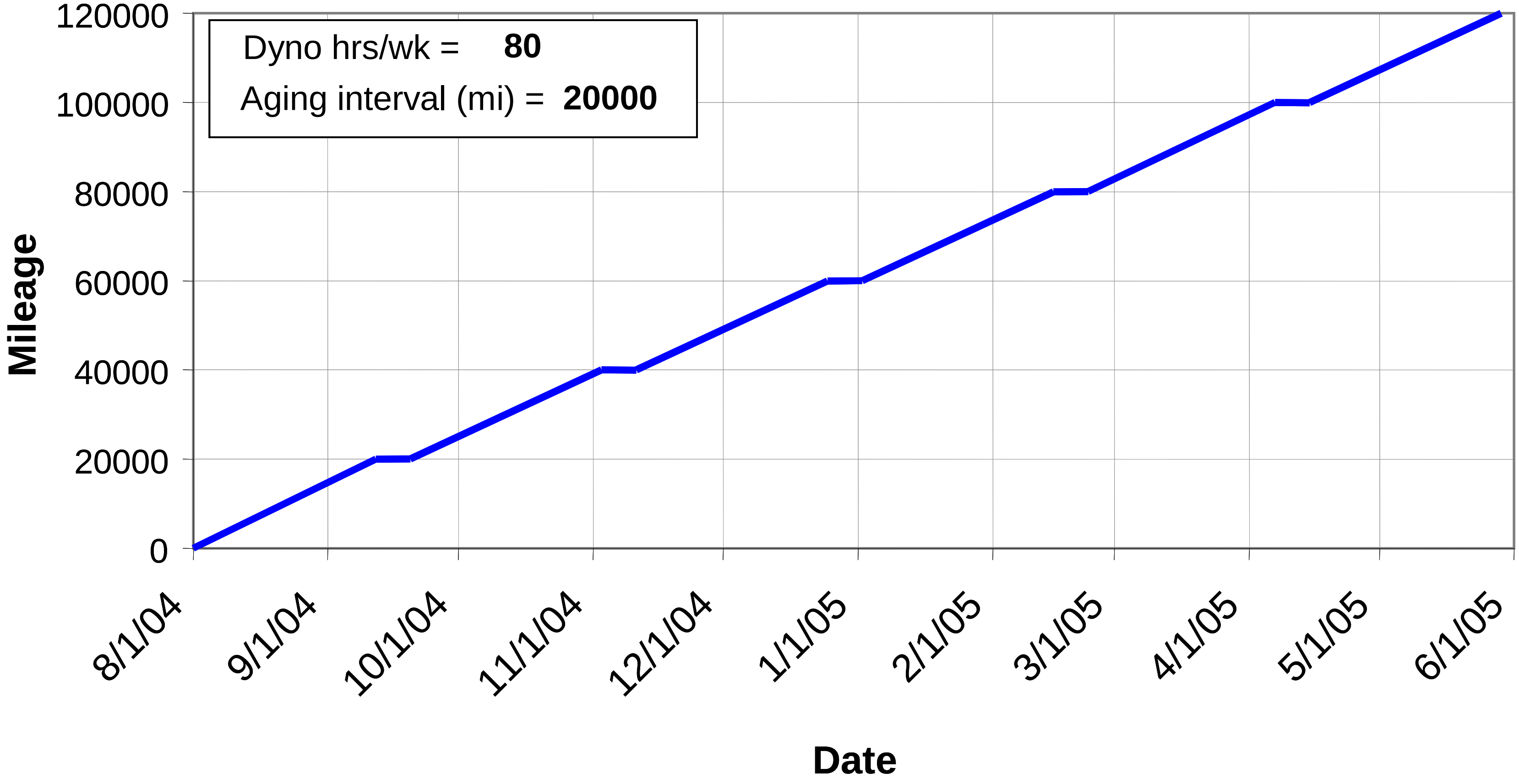
Task 3.4 Final Report Preparation

Durability Test Definition

Ford High Speed Cycle (HSC)



Durability Testing Schedule



Conclusions

- The objective of 0.07 g/mi NOx and 0.01 g/mi PM on the FTP was met with a fresh emission control system of Urea SCR and CDPF.
- System improvements included lower engine-out NOx and rapid system warm-up.
- Improvements were made to the urea dosing system.
- The SCR catalyst could withstand the temperatures associated with CDPF regeneration that also remove poisons (HC, S).
- Pre-production NOx and prototype NH_3 sensors were successfully tested.
- Co-fueling hardware was successfully demonstrated under cold conditions and potential nozzle durability issue was discovered.
- The cost of aqueous urea for LDD vehicles is minimized when bottled urea is used initially and co-fueling is phased in gradually.
- The project proceeded into Phase III (Durability Testing).

Acknowledgements

Ford

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FEV

Erik Koehler, Dean Tomazic

Exxon Mobil

Joan Axelrod, Rich Grosser, Marcus Moore, Mike Noorman, Charlie Schleyer

Backup Slides on Urea Economics

Details of Capital Cost for Co-fueling

- Dispenser supplier, nozzle supplier, and EM Fuels Marketing assisted with cost estimates for a complete co-fueled system.

Item	Est. Cost ($)
Dispenser, dual hose (basic)	6,000
Urea pumping system with heaters	4,500
Urea tank (140 gallon) with heaters	3,500
Hoses, nozzles, electronic level/signal	3,000
Freight and taxes (8%), utilities upgrade	3,500
Installation and startup	3,500
Administrative costs (permitting, ~10%)	2,500
Total	**26,500**

Details of Co-fueling Operating Expense

- Annual operating expense estimated from EM experience and additional urea system requirements.
- Cost shown assumes full heating for coldest climate use.

Item	Est. Cost ($/yr)
Maintenance	1,100
Property taxes (2% of capital)	220
Utilities	457
Total	**1,777**

Details of Bottled Aqueous Urea Cost

- Estimated costs for bottled urea as delivered to the retail location.

Item	Est. Cost ($/gal)
Manufacture + Distribution	0.60
Bottling	2.11
Delivery	0.95
Total	**3.66**