

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



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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



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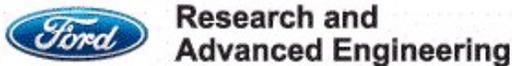
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DOE Ultra-Clean Fuels Program

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



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

Subcontractors



Phase II - System/component optimization phase (July 02-July 04)

Define final system hardware components

Deliver NOx and PM performance data from fresh system



Catalyst Suppliers

ENGELHARD

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



Johnson Matthey



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

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SCR Catalyst Development

- Durable, high NO_x conversion from 150° to 600°C with low N₂O 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



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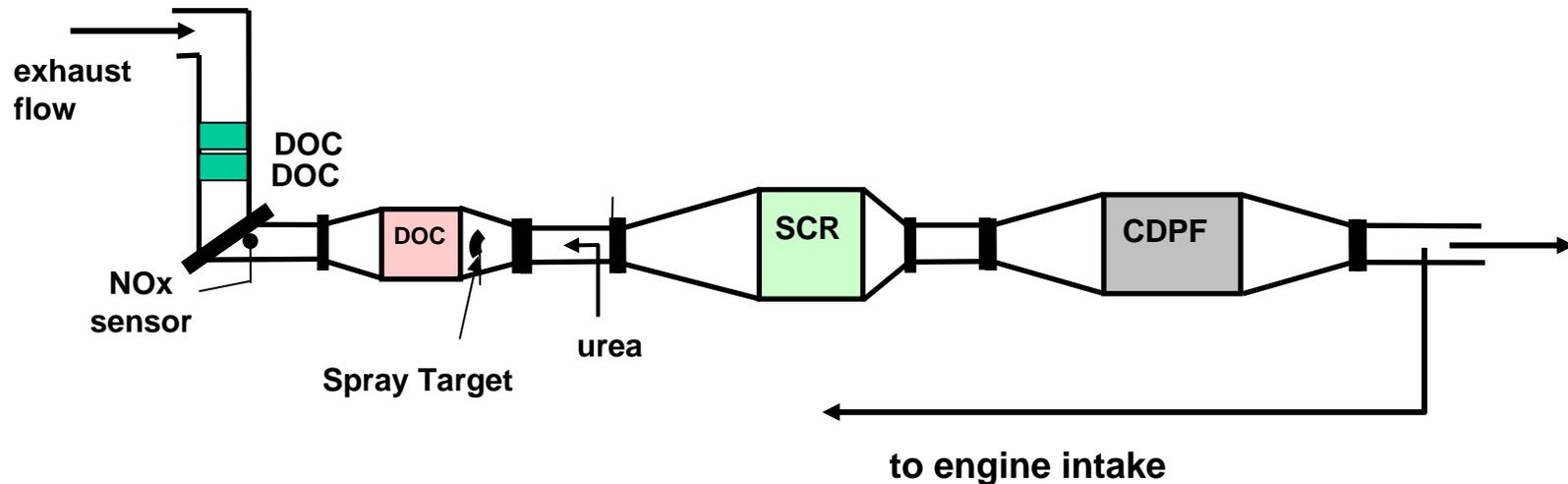
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LDT Exhaust System

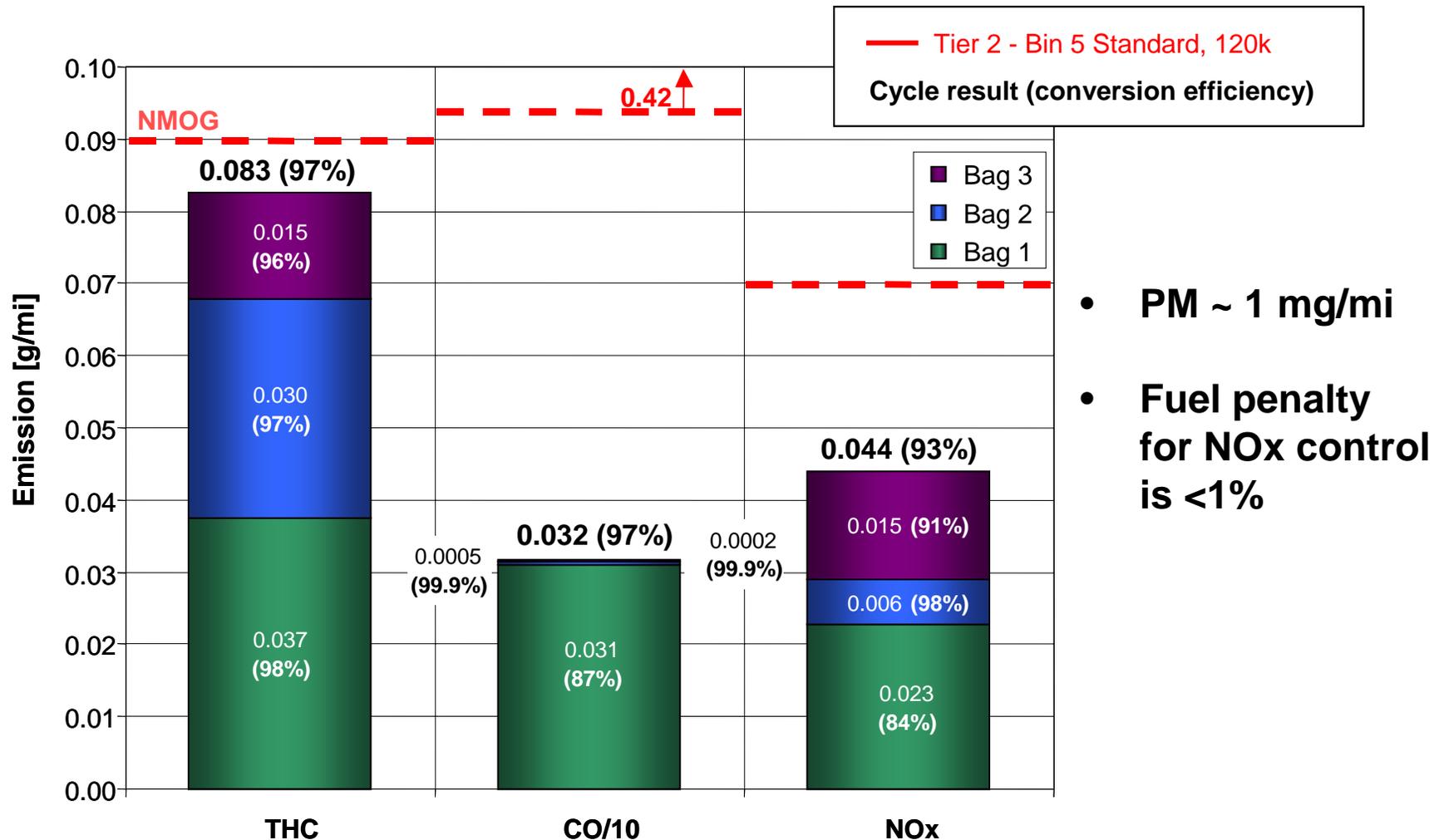
>90% FTP NO_x conversion, 0.05 g/mi TP NO_x



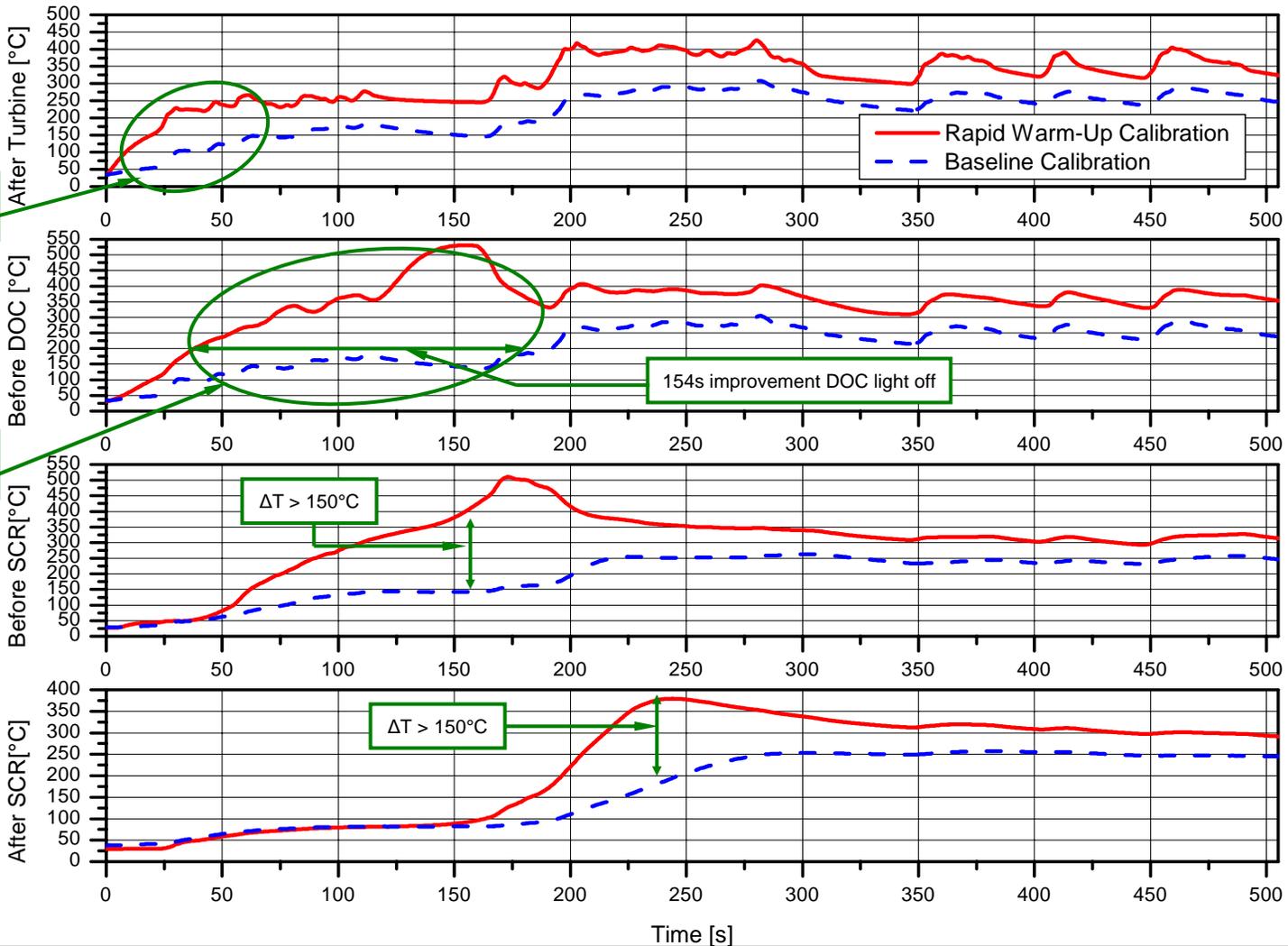
- Engine-out NO_x lowered by 40% with increased EGR
- Low tailpipe NO_x achieved with rapid warm-up strategy
 - lower thermal mass upstream of catalyst system
 - engine calibration changes during cold start (post injection & inc. idle speed)

FTP-75 Tailpipe Emissions and Conversions

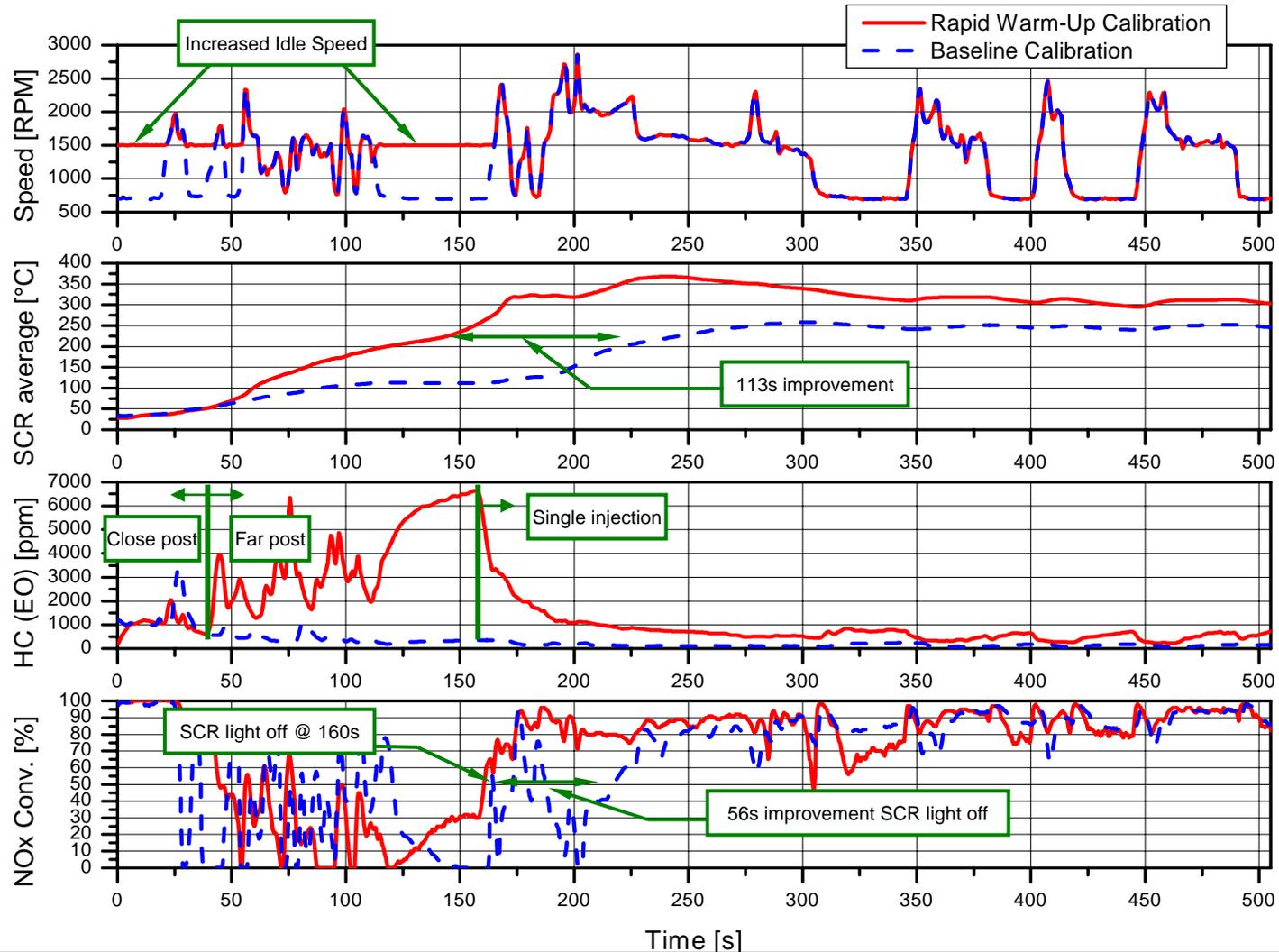
(with fresh catalysts on engine dyno)



Rapid Warm-up - *Improvement*



Rapid Warm-up - *Improvement*



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System Durability



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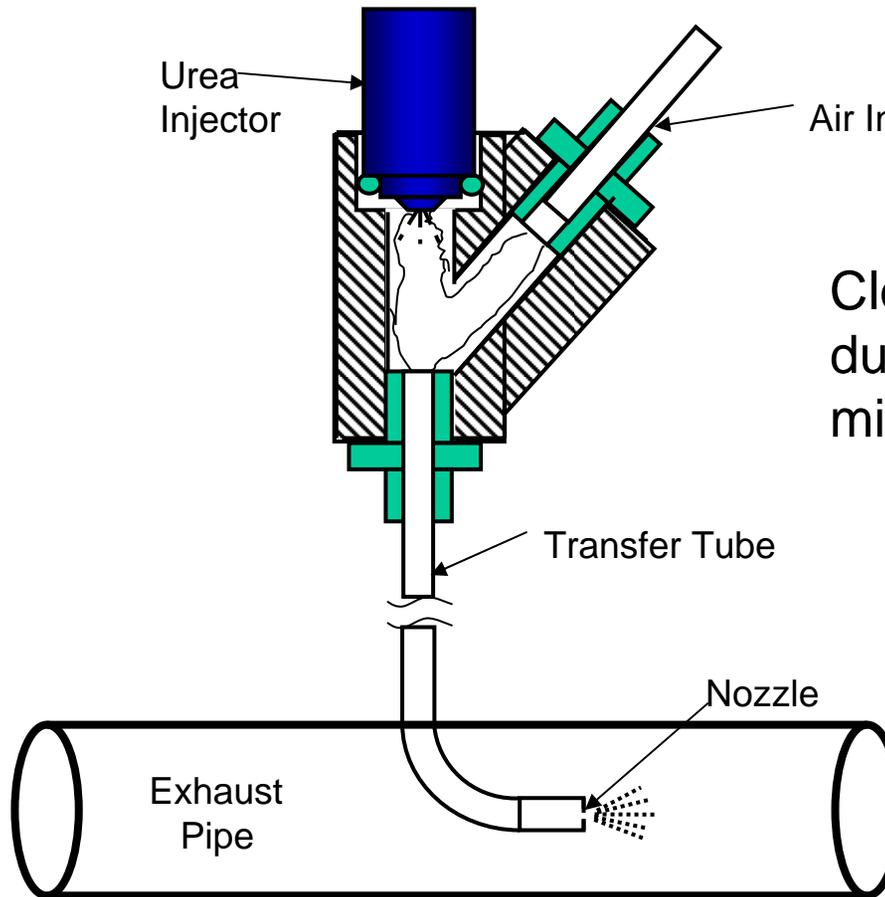


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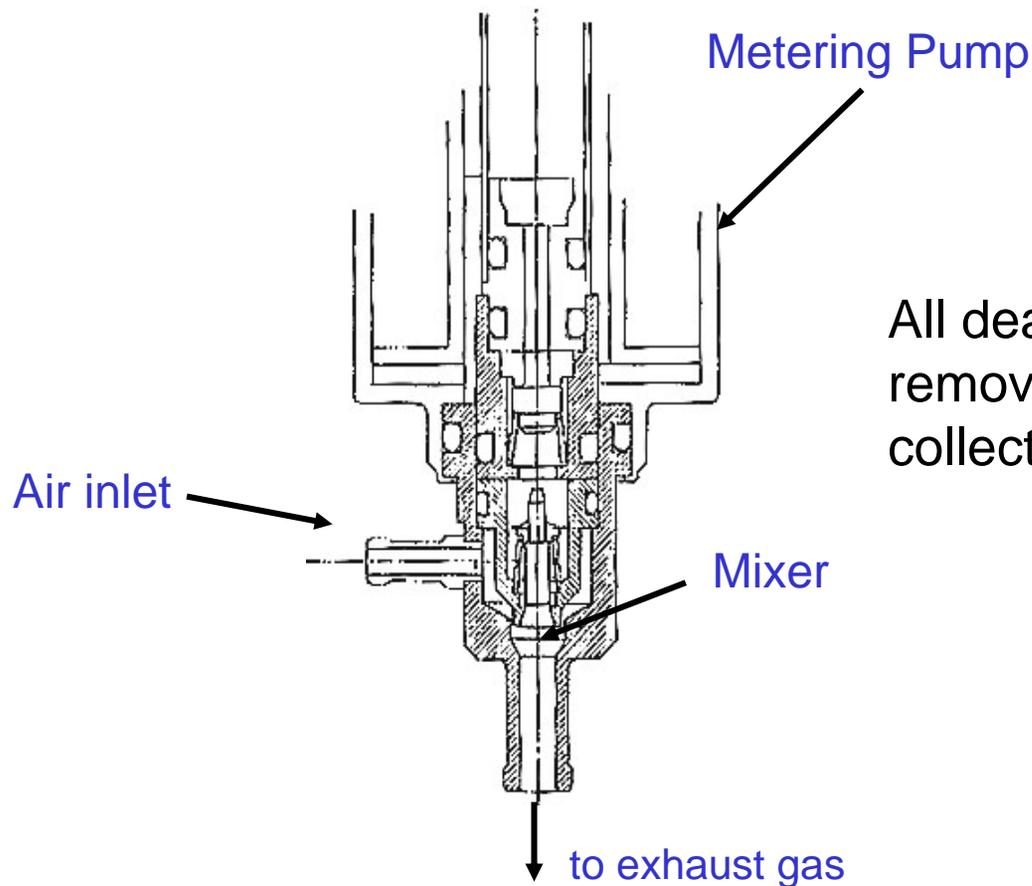
Urea Dosing System: Previous Urea Injection System



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.



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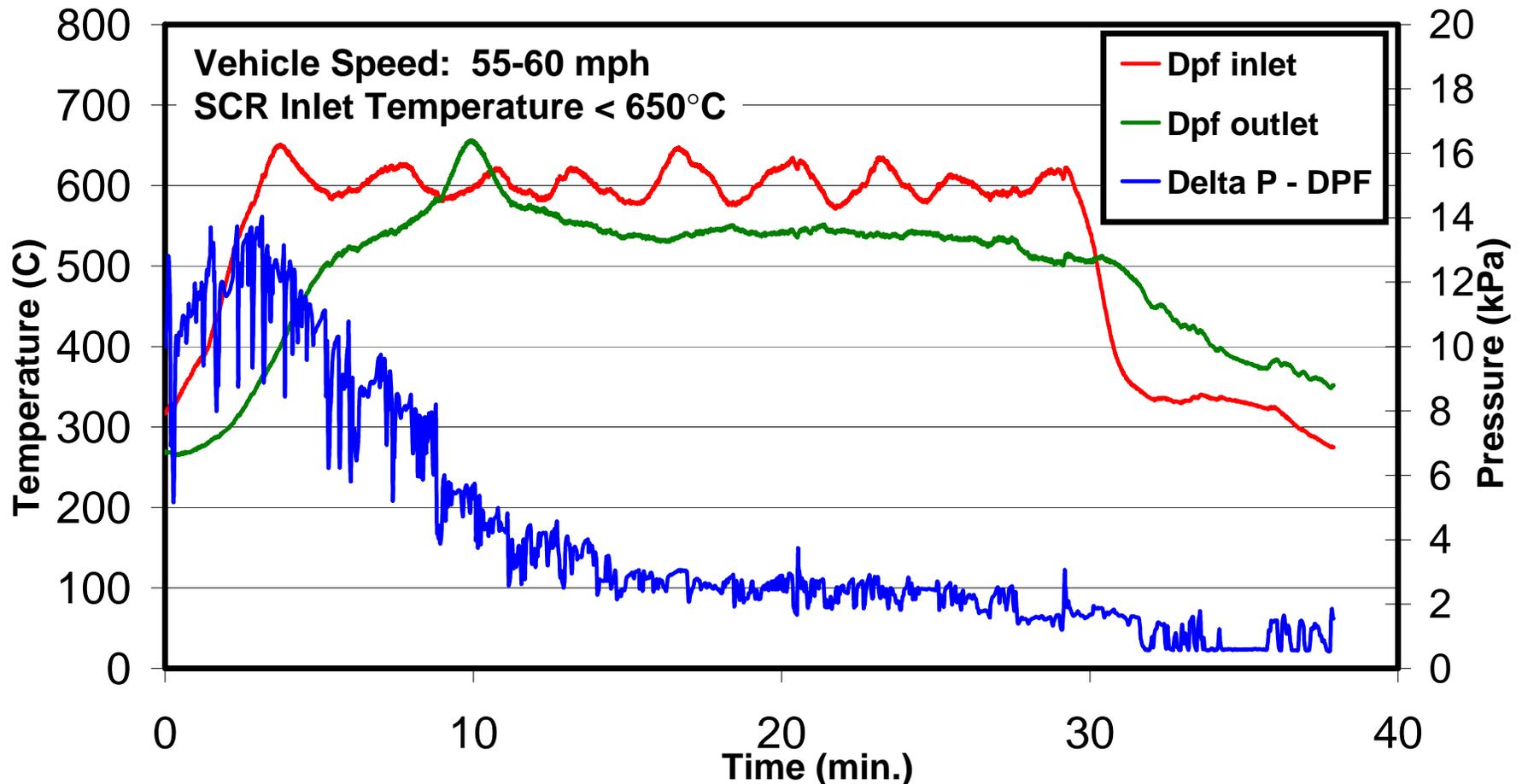


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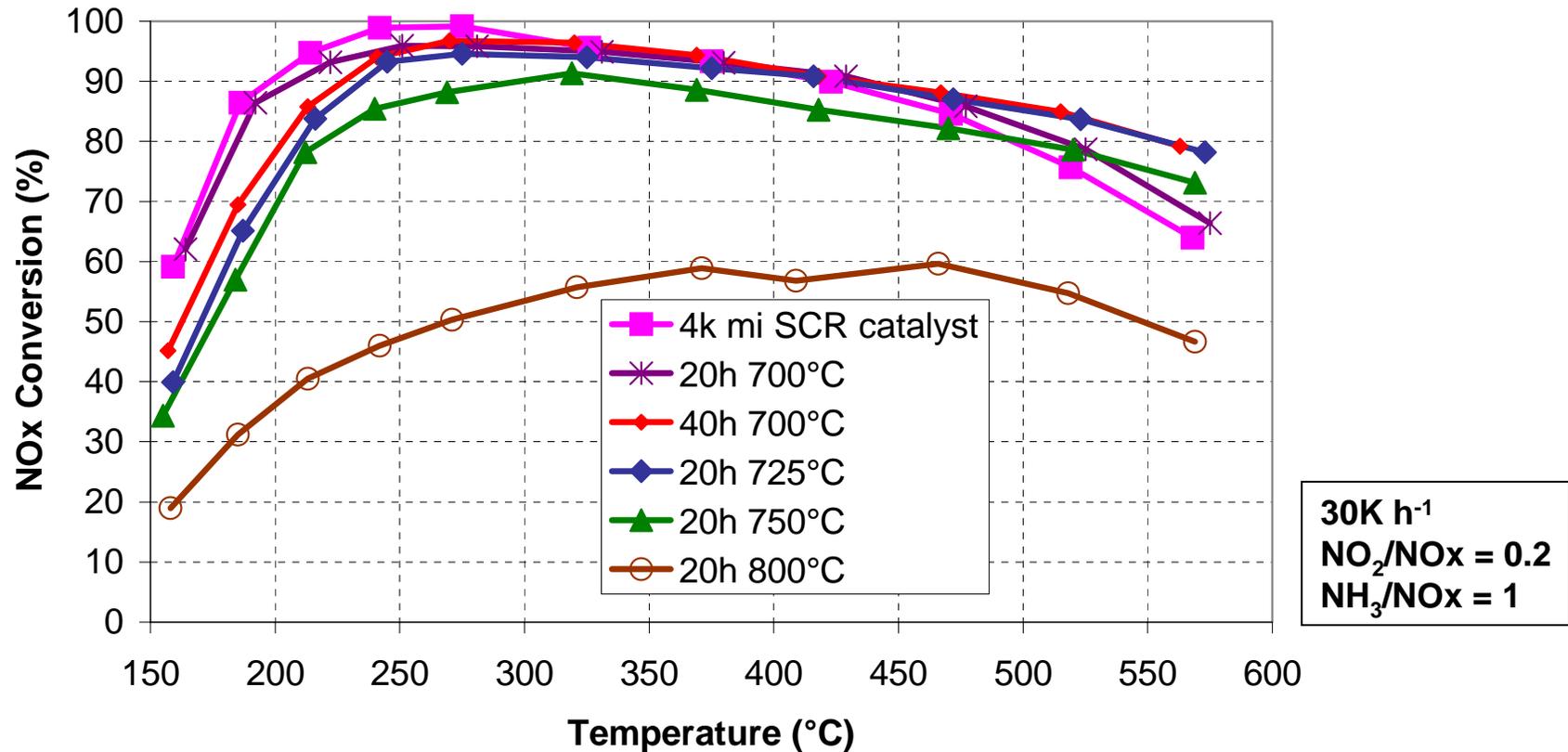


SCR Catalyst Durability: LDT CDPF Regeneration



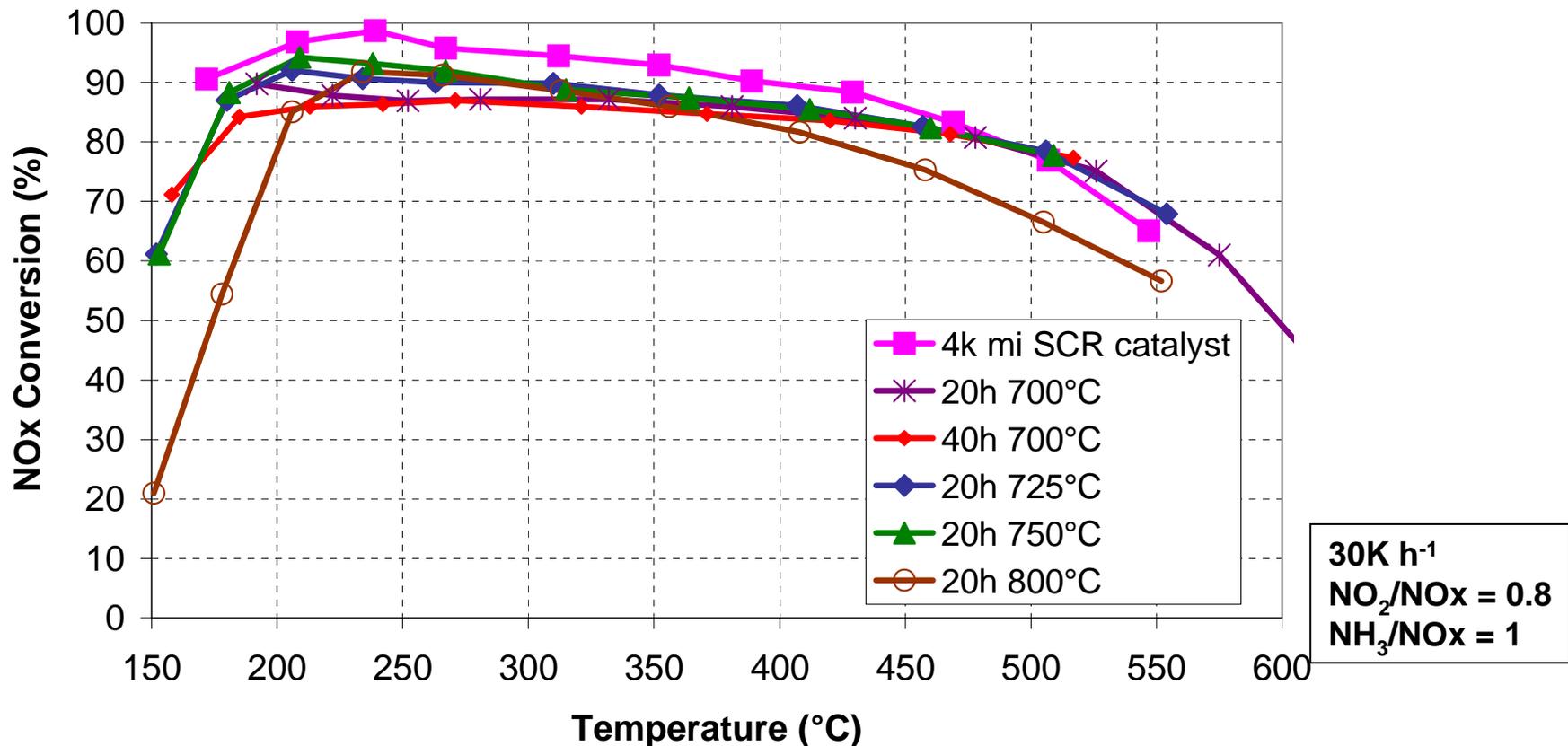
- SCR activity was identical before and after regeneration

SCR Catalyst Durability: High Temperature



- With 20% NO₂/NO_x feed, the catalyst is durable to 750°C

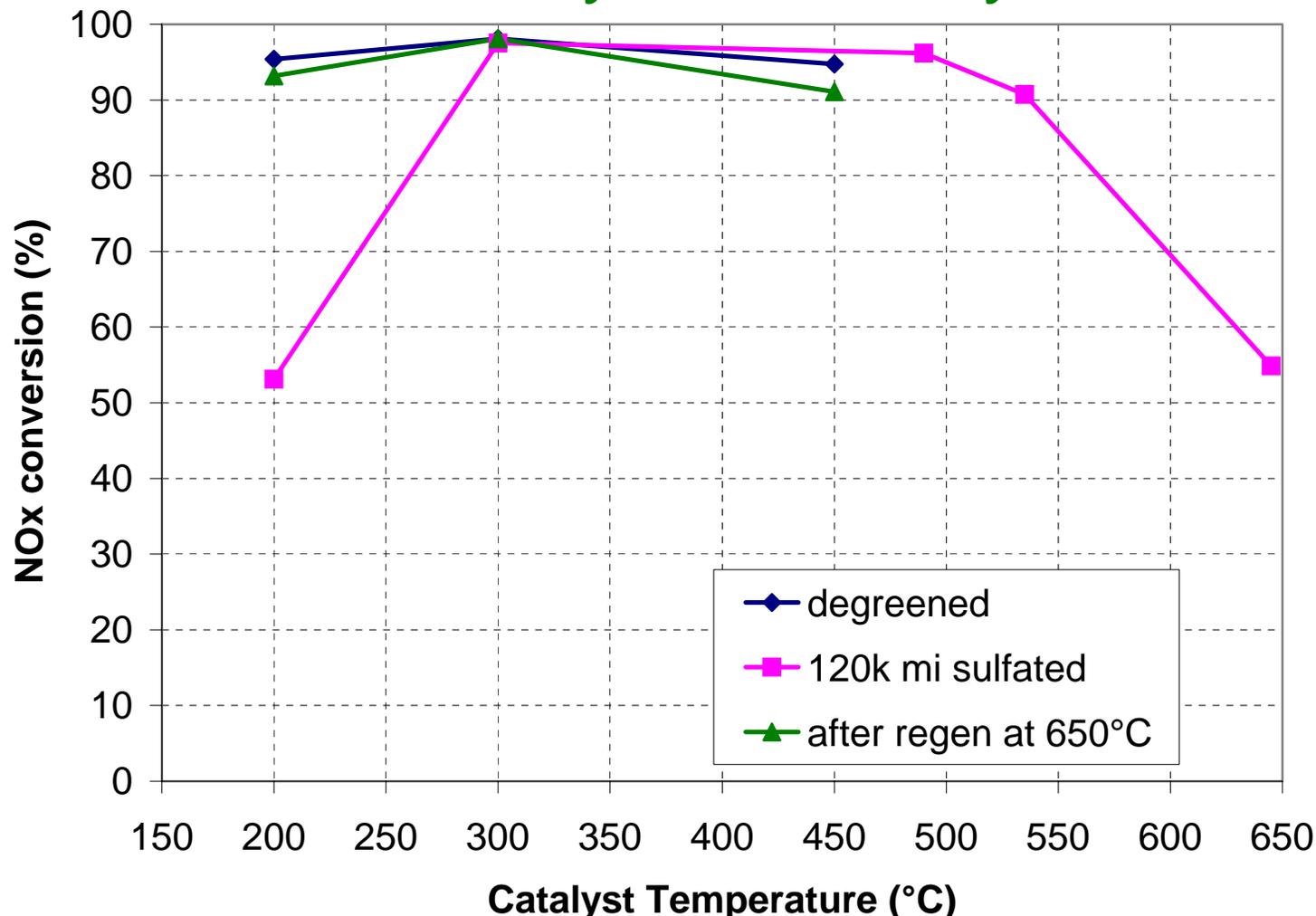
SCR Catalyst Durability: High Temperature



- With 80% NO₂/NO_x feed, the catalyst is durable to 800°C



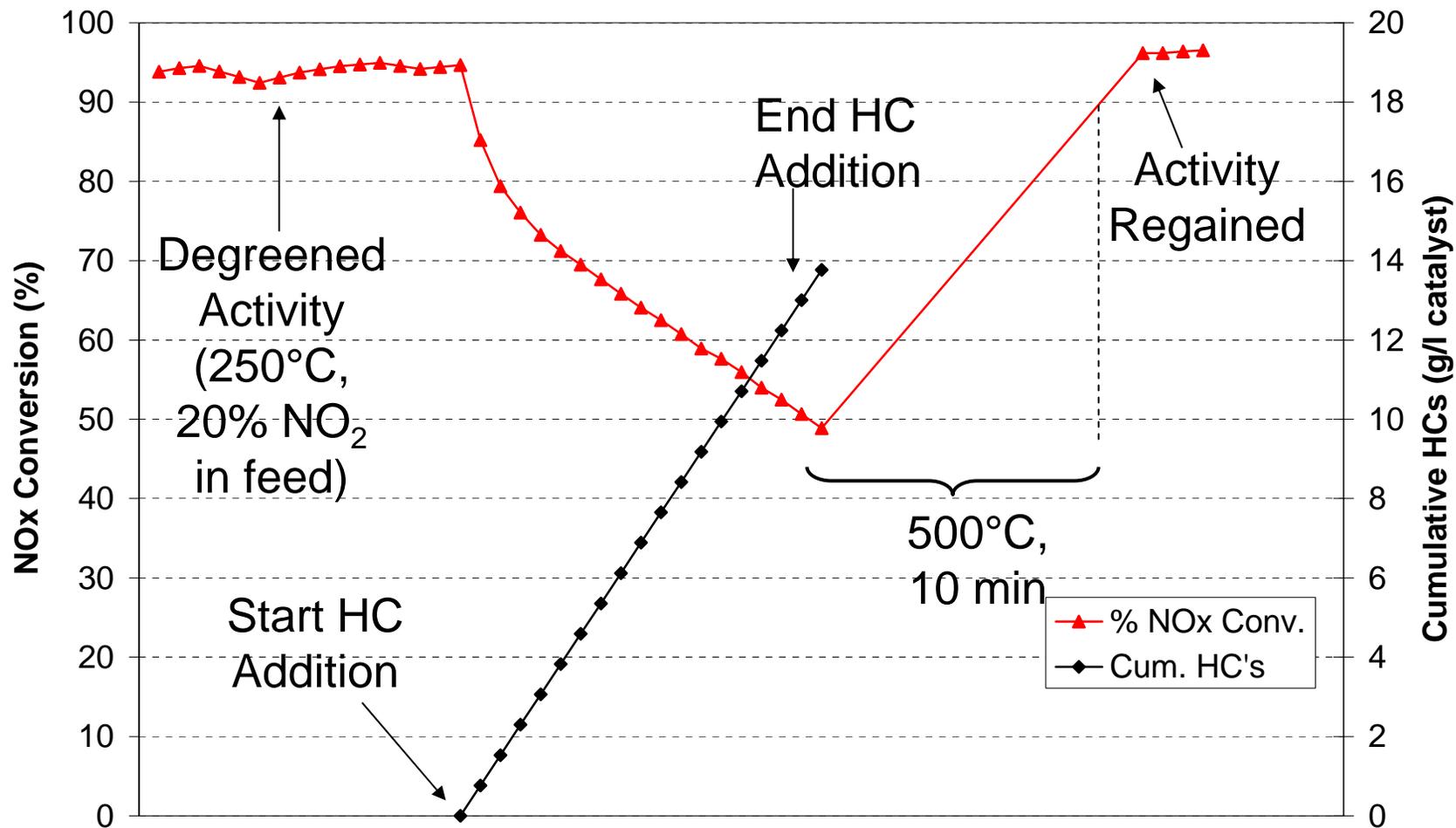
SCR Catalyst Durability: Sulfur



- 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



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Emission Sensors

NO_x:

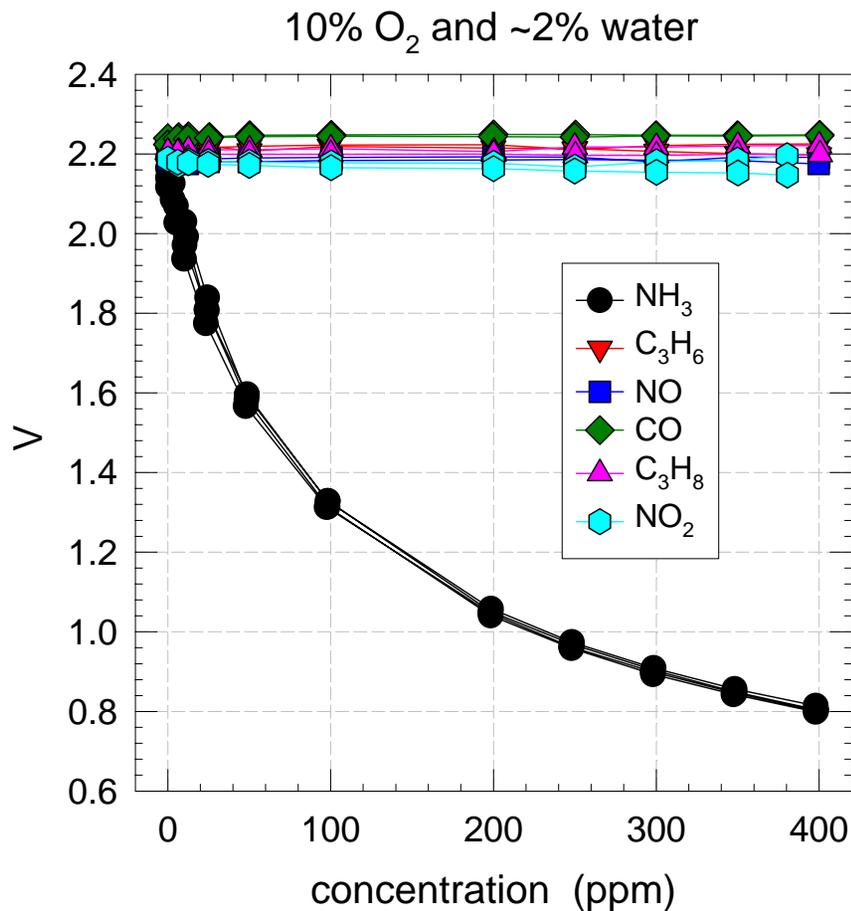
- Sensors used in monitoring both engine out and tailpipe NO_x levels
- Pre-production prototypes developed by a supplier with no major issues
- Production-intent sensors to be used for durability studies

NH₃:

- Used in monitoring NH₃ slip
- Prototypes under development by a supplier
- To be included in durability studies



Laboratory Data for Prototype NH₃ Sensor



- Good NH₃ sensitivity with little direct sensitivity to interfering gases such as CO, HC, NO_x and O₂
- Some sensitivity to H₂O



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Urea Infrastructure Study



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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)

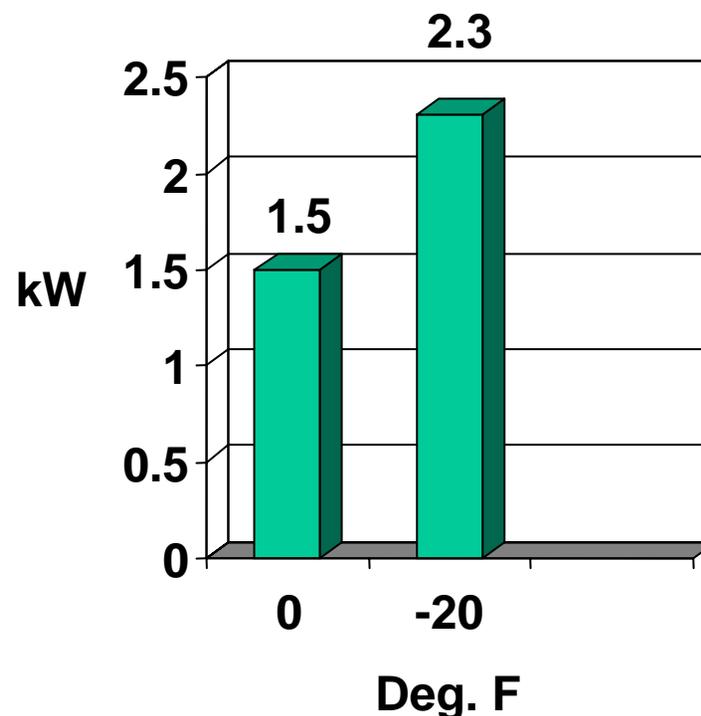
Recommendations

- Heater system is feasible
- Three heater system approach is anticipated for urea heating in US:
 - no heaters for temperatures $> 12^{\circ}\text{F}$
 - line heaters only for temperatures $> 5^{\circ}\text{F}$
 - full heaters for temperatures to -20°F

Issues

- Concerns over power outage and system malfunction

Power Consumption



Urea Infrastructure Economics

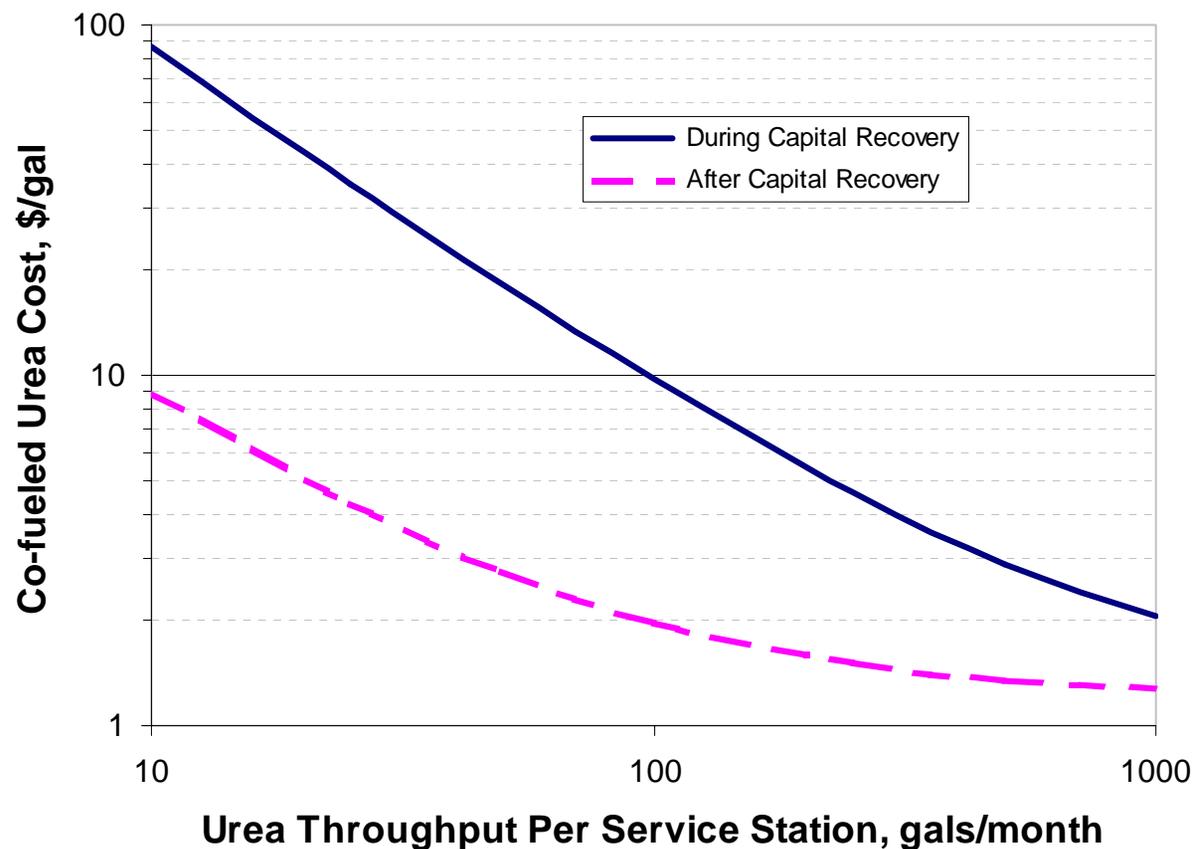
Background:

- 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



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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

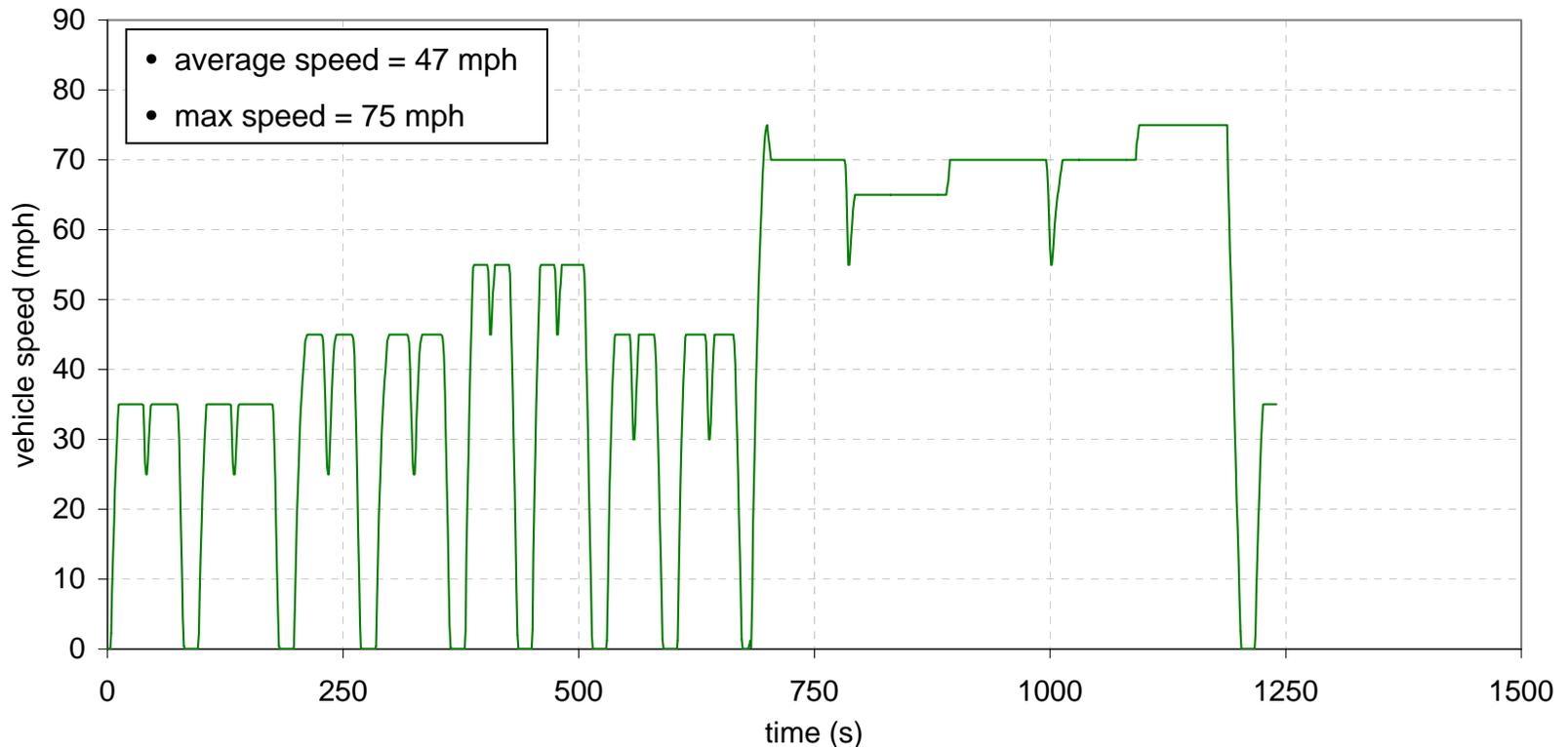
Task 3.3 Post Durability Evaluation

Task 3.4 Final Report Preparation

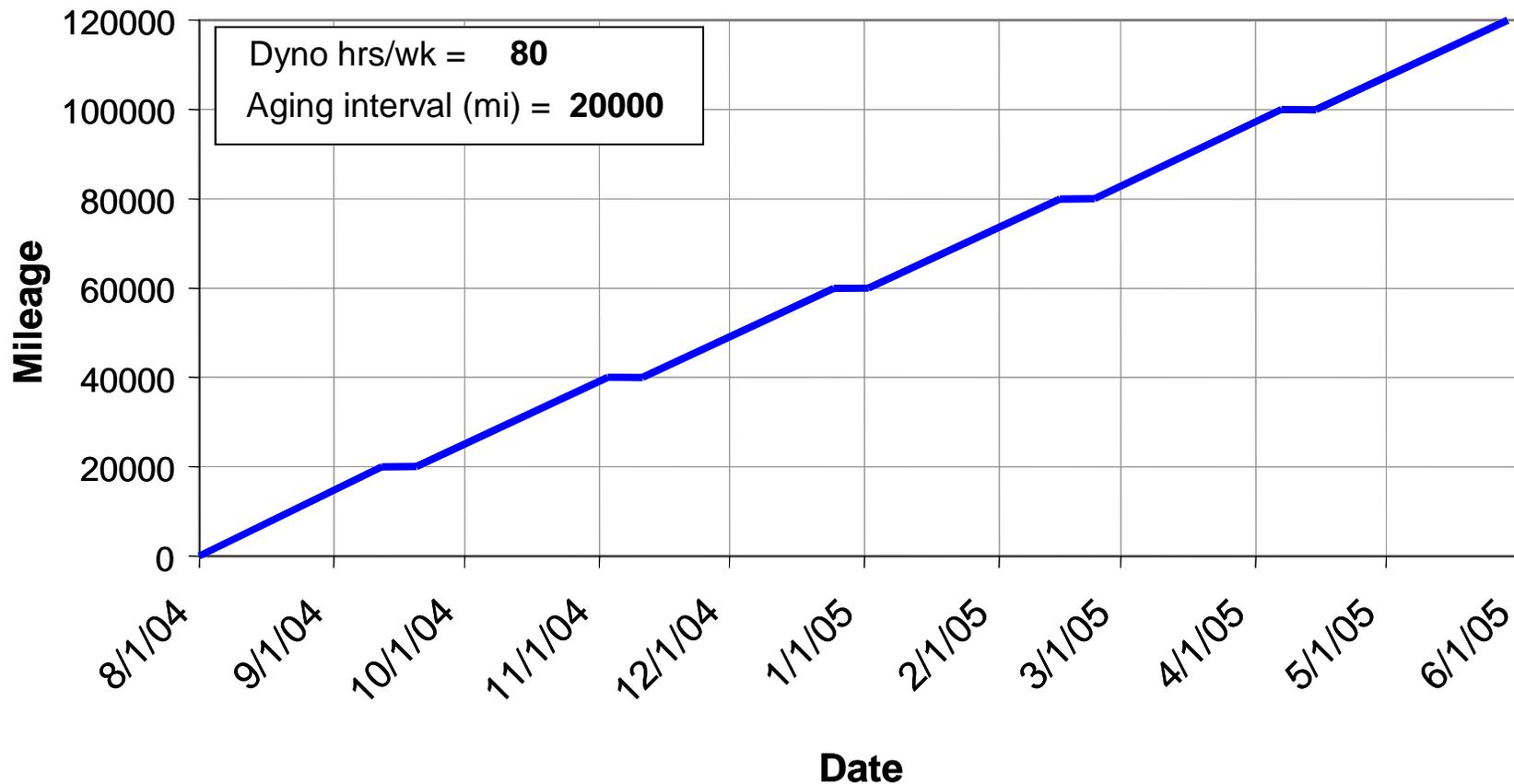


Durability Test Definition

Ford High Speed Cycle (HSC)



Durability Testing Schedule



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Conclusions

- The objective of 0.07 g/mi NO_x 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 NO_x 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 NO_x and prototype NH₃ 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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Exxon Mobil

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Backup Slides on Urea Economics



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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

