Combination and Integration of DPF – SCR Aftertreatment Technologies

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ACE025

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OVERVIEW

Timeline

- Start – Oct 2008
- Finish – Sept 2012

Barriers

- Barriers addressed
  - Heavy truck thermal efficiency
  - Cost effective emission control
  - Combined NOx and PM emissions

Budget

- Total planned project funding
  - $1.6M DOE share
  - $1.6M I.K. Contractor share
- $875K received through FY11

Partners

- Primary Partner: PACCAR
  - PACCAR Technical Center
- DAF Trucks (operating as an extension of PACCAR)
  - Utrecht Univ. supporting DAF
- Project Lead: PNNL

Objective is to fundamentally understand the integration of SCR & DPF technologies for HDD

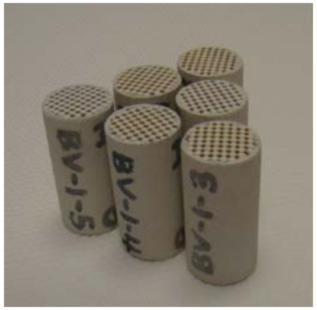
- Determine system limitations, define basic requirements for efficient/effective operation and integration with engine
- Develop an understanding of …
  - optimal loading of SCR catalyst for maximizing NO_x reduction while maintaining acceptable ΔP and filtration performance
  - proper thermal and reactive management of the system for efficient NO_x reduction along with maximizing passive soot oxidation capacity
- Motivation for integration: to target a reduction of cost and volume of the engine aftertreatment systems via inclusion of SCR and DPF functionalities into a single entity.

MILESTONES

- Demonstrate integrated DPF/SCR on 2 cm dia. elevated porosity filter (19 mo.) – complete
- Discussions with manufacturer on pathway to fabricate integrated DPF/SCR for vehicle demonstration (33 mo.) – complete
- Demonstrate performance of an integrated DPF/SCR system on an elevated porosity wall-flow filter sample on a diesel engine exhaust slip stream (39 mo.) – complete
- Demonstrate a 15+ cm diameter coated wall flow integrated DPF/SCR system can be prepared that has similar dispersion of catalyst(s) as a ~2 cm diameter wall flow coated filter – later this year
- Demonstrate performance of an integrated DPF/SCR wall-flow filter on diesel engine (48 mo.) – later this year [engine (DAF) and truck** (PACCAR)]; **pending successful engine demonstration

APPROACH/STRATEGY

- First key barrier to successful system implementation: ΔP
  - Solutions:
    1. Higher porosity substrate
    2. Refined wash-coating technique



1. High porosity (UHP) substrate
   - Cordierite: Corning developmental UHP substrate
   - Aspiring to include SiC, ACM in engine slip-stream investigations
2. BASF refined wash coating technology
   - Multiple iterations of coated parts acquired for study
   - Good working relationship with BASF’s HD Systems R&D group

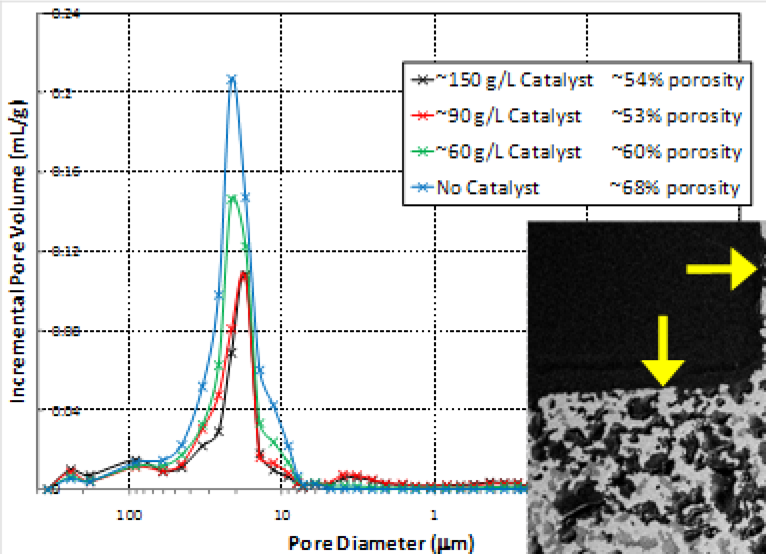
APPROACH/STRATEGY

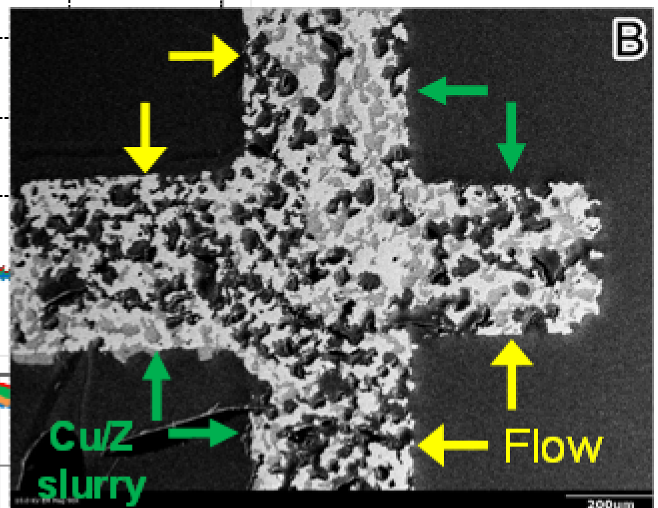
- Highly evolving field of work (mostly LDD, some HDD)*
- This effort currently focused on:
  - **Optimizing SCR catalyst washcoat**
  - **Facilitating passive soot oxidation**

*see back-up slides for overview of recent field of work

- Working relationship with BASF (HD Systems Development)
  - SCR catalyst (Cu/Z) expertise
  - Washcoating, manufacturability
  - UHP cordierite substrate sample coating (cores, bricks)
- Flow restriction concerns
  - ΔP: SCR/DPF > SCR + cDPF (demonstrated by prior efforts)
  - Maximize NO_x reduction performance, maximize PM filtration performance, and minimize flow restriction simultaneously is the challenge

Work Previously Presented

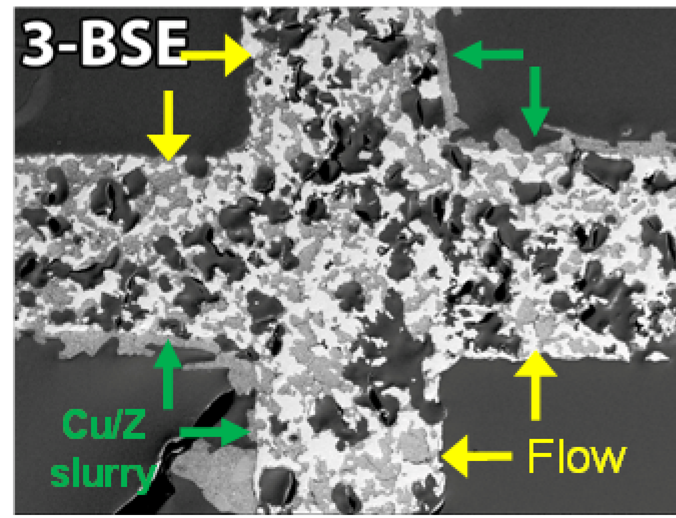


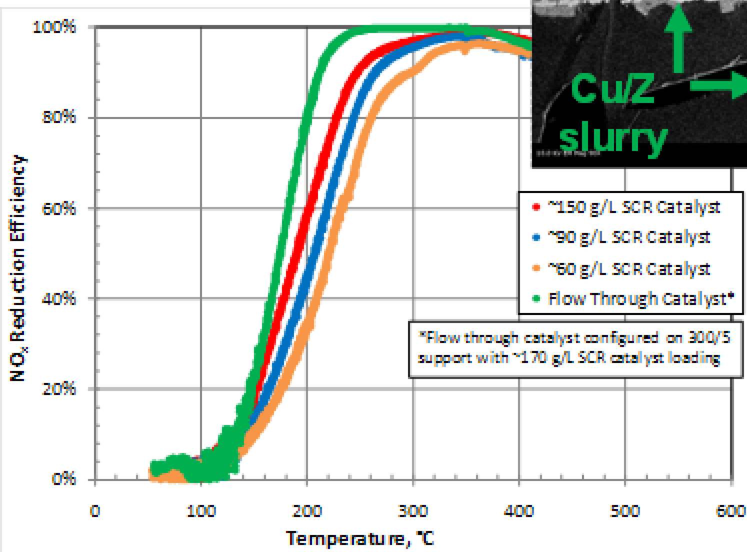


90 g/L

>90 g/L deposits largely on channel wall, NOT within porous structure

150 g/L

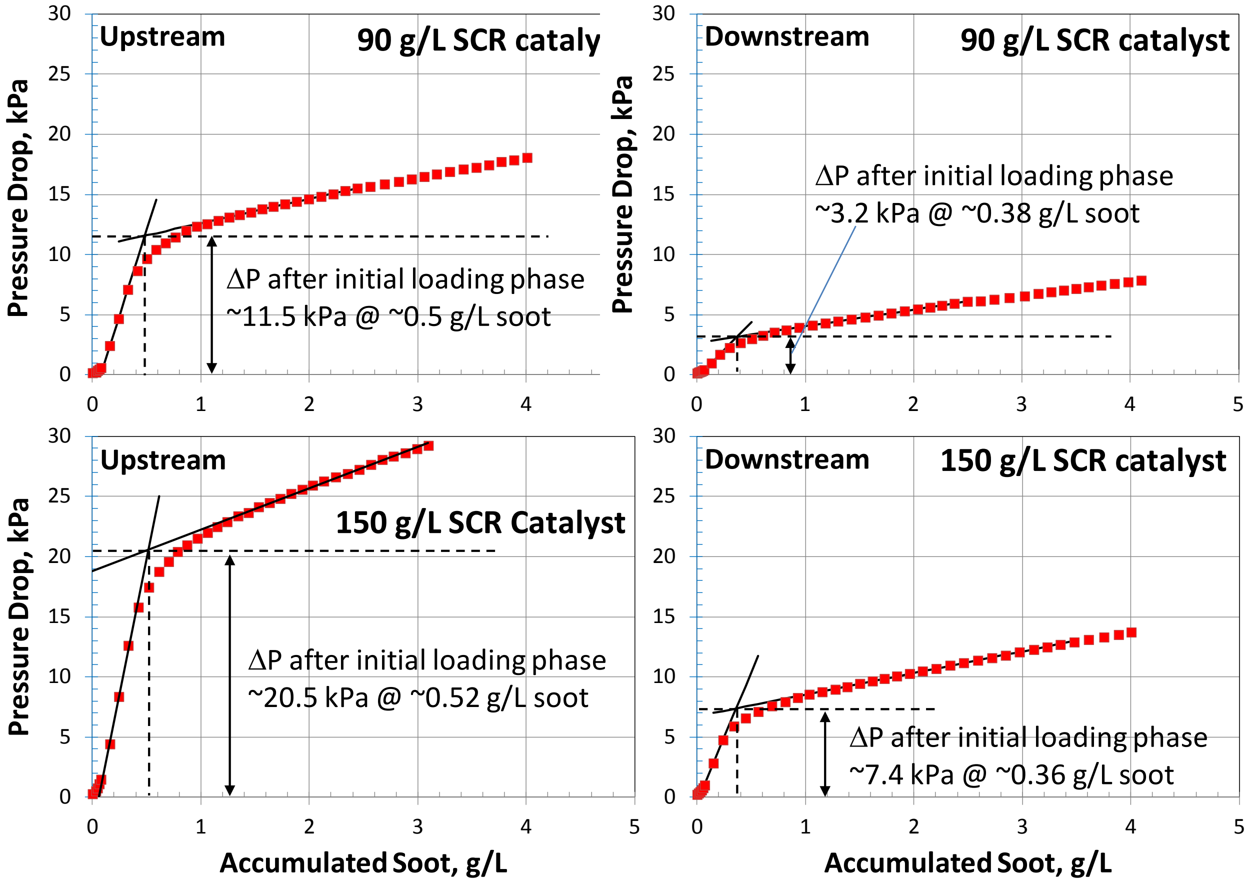




Catalyst most effectively utilized within porous wall structure

TECHNICAL ACCOMPLISHMENTS

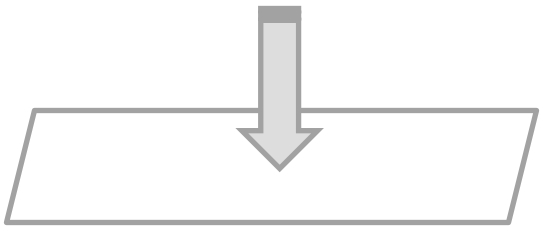
(2003 Jetta, ~300°C, 55k GHSV)



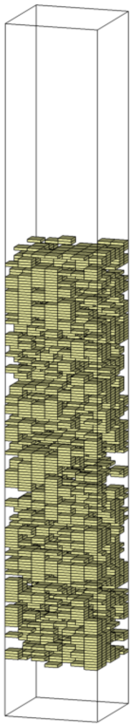
- Both ***amount*** and ***location*** of SCR catalyst have measureable significant impact on dynamic permeability of filter during soot loading

Modeling of wall-scale transport effects

- Single flat wall with exhaust approaching in the normal direction
- Channel scale transport effects & axial variations are ignored
- Simplified SCR reaction network developed at PNNL for current Cu-CHA SCR catalyst
- Commercial flow-through parts used to develop SCR model loaded to ~170 g/L
- Simplified porous media with similar porosity and tortuosity of the SCRF used in experiments
- 90 g/L of catalyst distributed evenly throughout the porous wall + 60 g/L placed on down-stream wall surface
- Soot oxidation kinetic model by Messerer et al, 2006
- Assumed fresh (very reactive) soot
- *Conclusions dependent upon validity of assumptions and kinetics used*



350°C
4 g/L soot
150 g/L catalyst
500 ppm NO_2
500 ppm NO
35,000 GHSV
ANR = 1

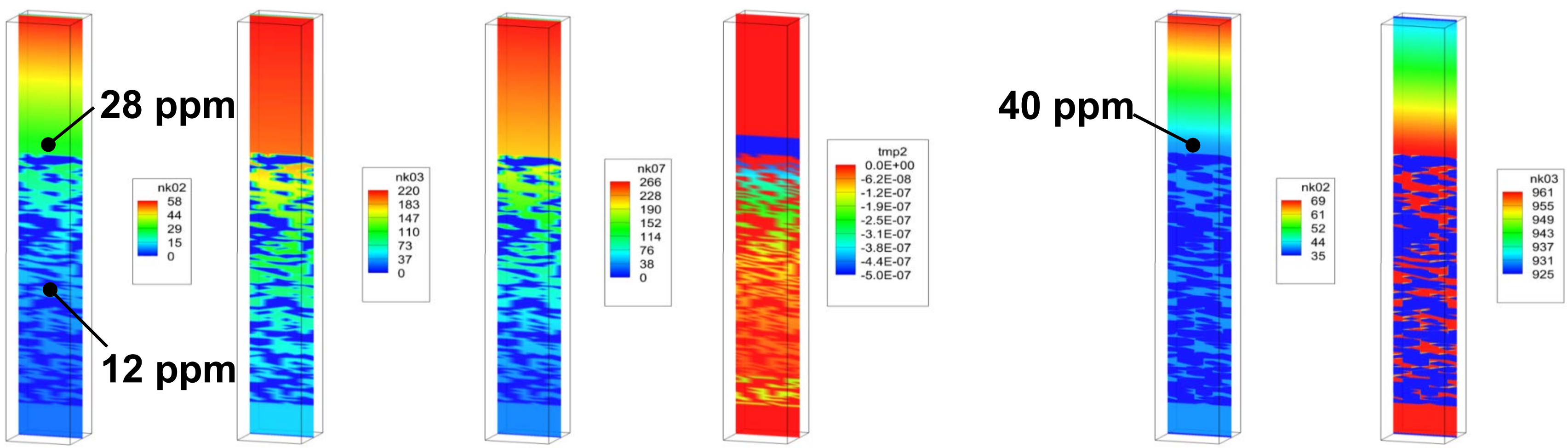


TECHNICAL ACCOMPLISHMENTS

Modeling of wall-scale transport effects

With SCR — NO_2 [ppm], NO [ppm], NH_3 [ppm], NO_2 rate

No SCR — NO_2 [ppm], NO [ppm]



Outlet: 6 ppm NO_2, 46 ppm NO, 33 ppm NH_3

Soot oxidation: 8.9 g/s L
NO_x reduction: 95%

Outlet: 40 ppm NO_2, 960 ppm NO

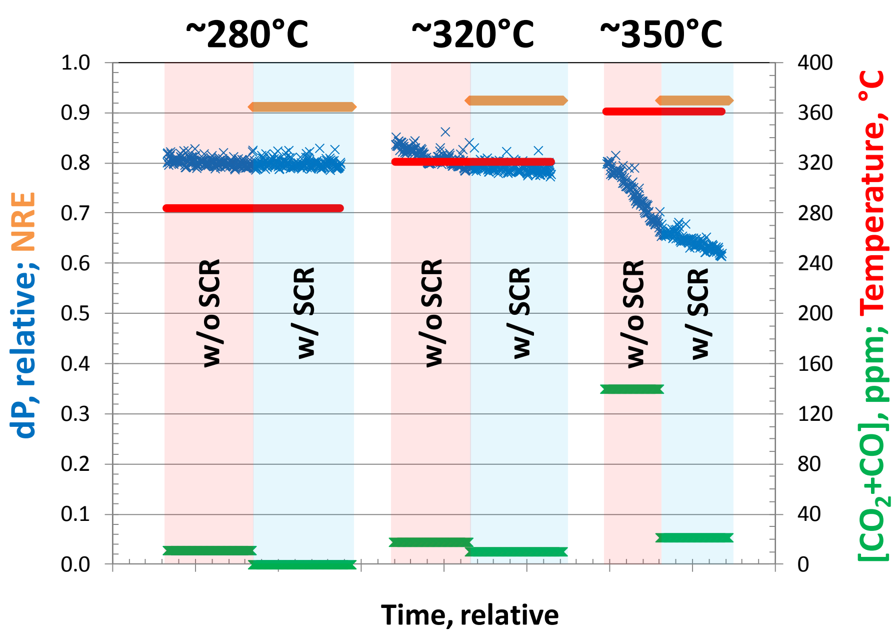
Soot oxidation: 11.3 g/s L
NO_x reduction: 0%

- **SCR reduces soot oxidation rate by lowering upstream NO_2 concentrations**
- A mild NO_2 gradient exists across the porous SCRF wall, indicating that catalyst placement on the downstream side of the wall is somewhat advantageous

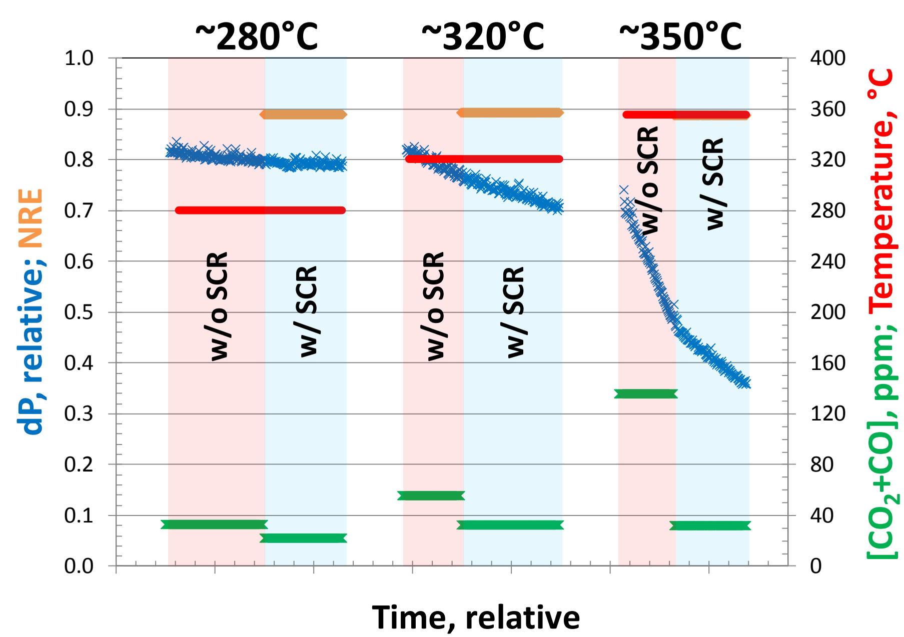
TECHNICAL ACCOMPLISHMENTS

Pulsed Oxidation Studies – 150 g/L SCR catalyst

- Effect of NO_2 concentration – 200 ppm (left) versus 500 ppm (right)
- 1000 ppm NO_x, ANR = 1, 35k GHSV
- **Increased NO_2 minimizes PSO-inhibiting effect of SCR processes**



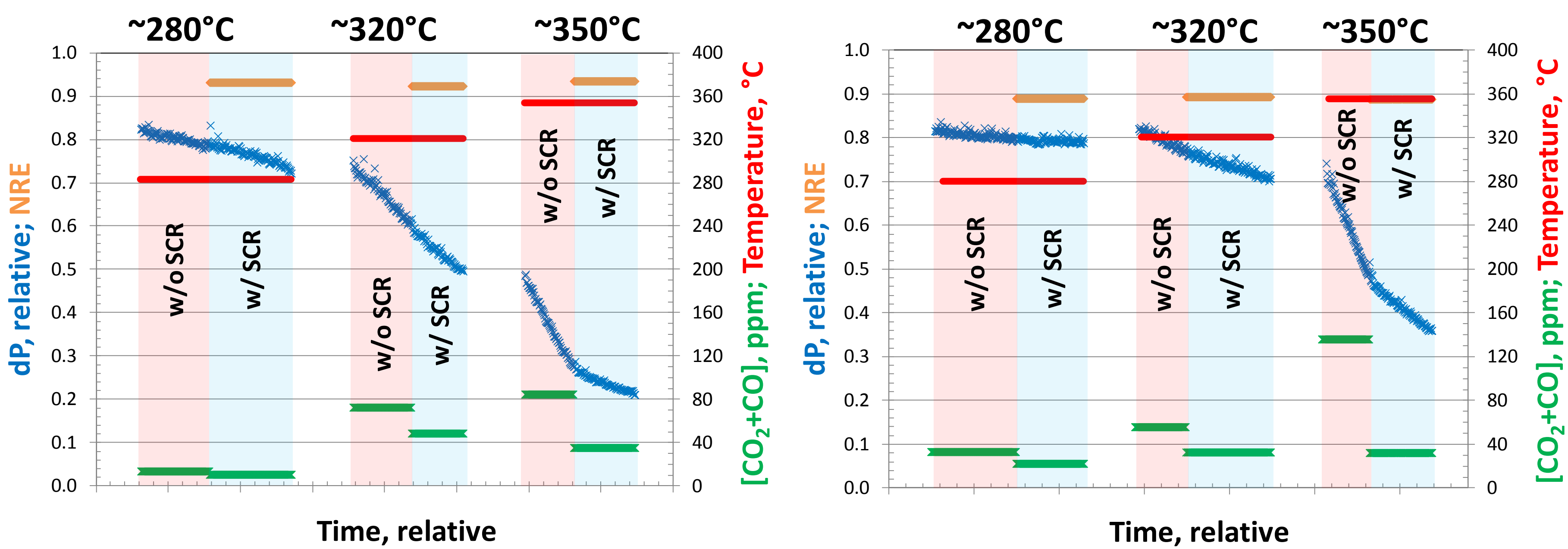
200 ppm NO_2



500 ppm NO_2

Pulsed Oxidation Studies

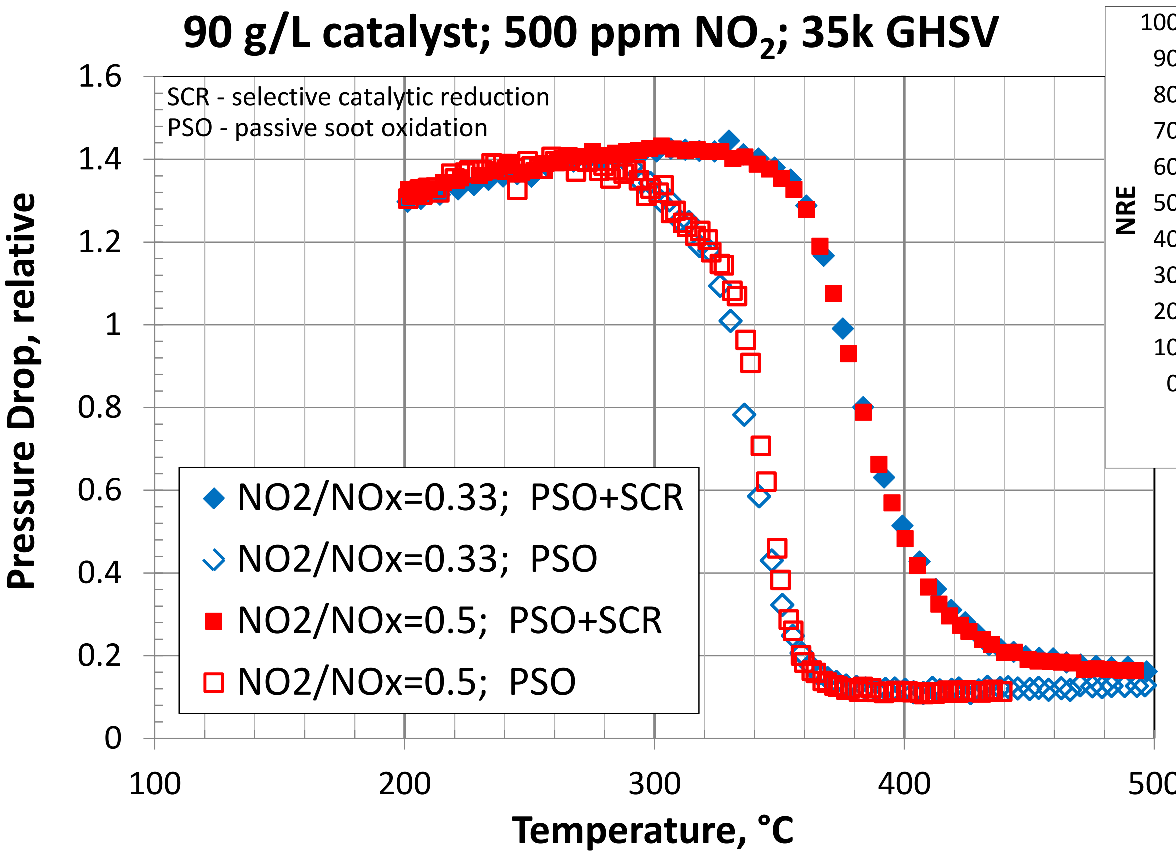
- Effect of catalyst loading – 90 g/L (left) versus 150 g/L (right)
- 500 ppm NO_2, 1000 ppm NO_X, ANR = 1, 35k GHSV
- **Increased PSO observed <350°C with 90 g/L versus 150 g/L**

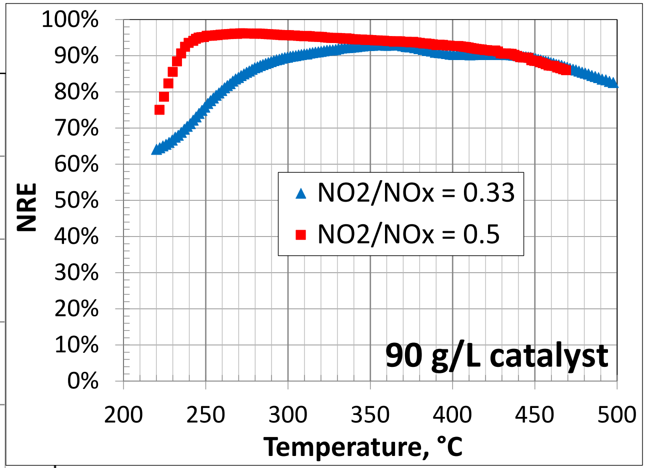


90 g/L SCR catalyst

150 g/L SCR catalyst

TPO – Temperature Programmed Oxidation



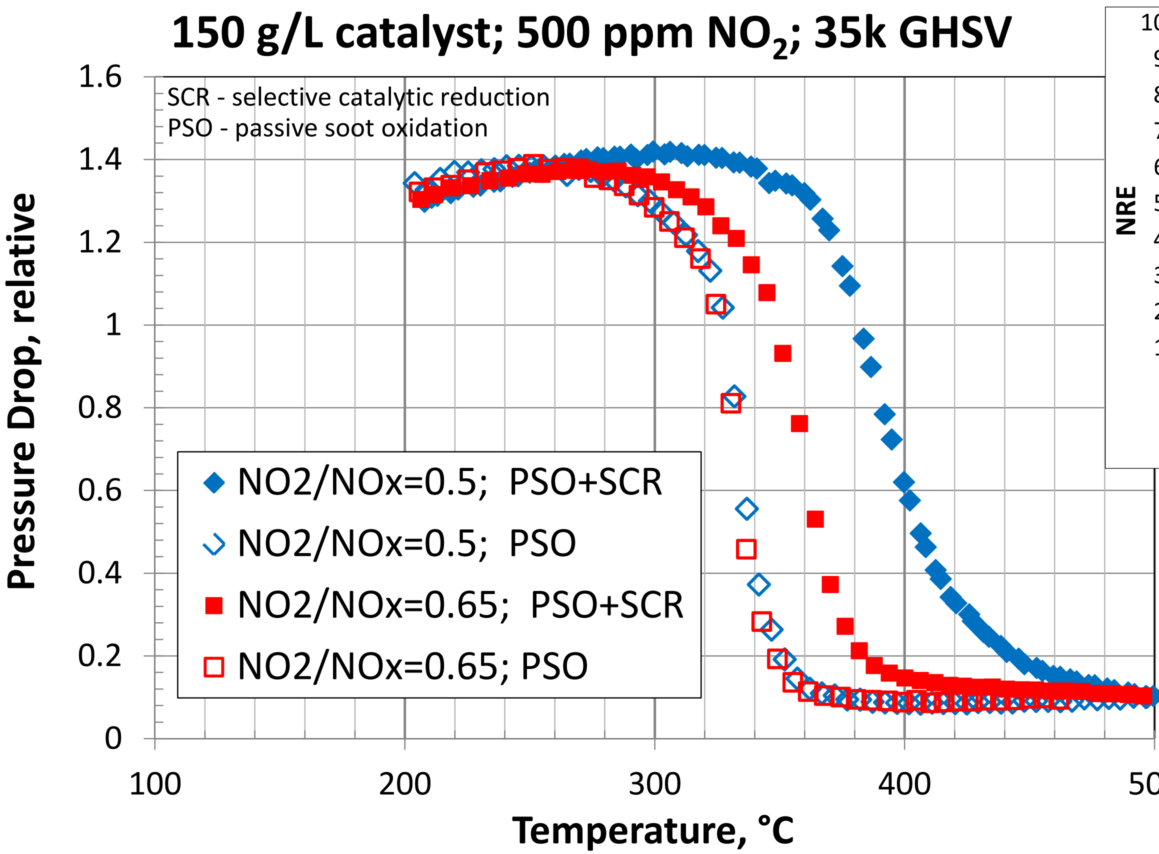


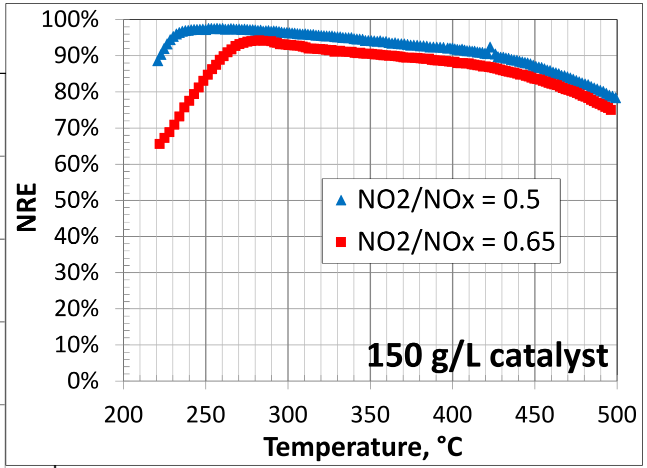
- Negligible impact of NO_2/NO_x fraction <0.5
- Passive soot oxidation retardation ~40°C

- ANR = 1
- 4 g/L soot loading

TECHNICAL ACCOMPLISHMENTS

TPO – Temperature Programmed Oxidation

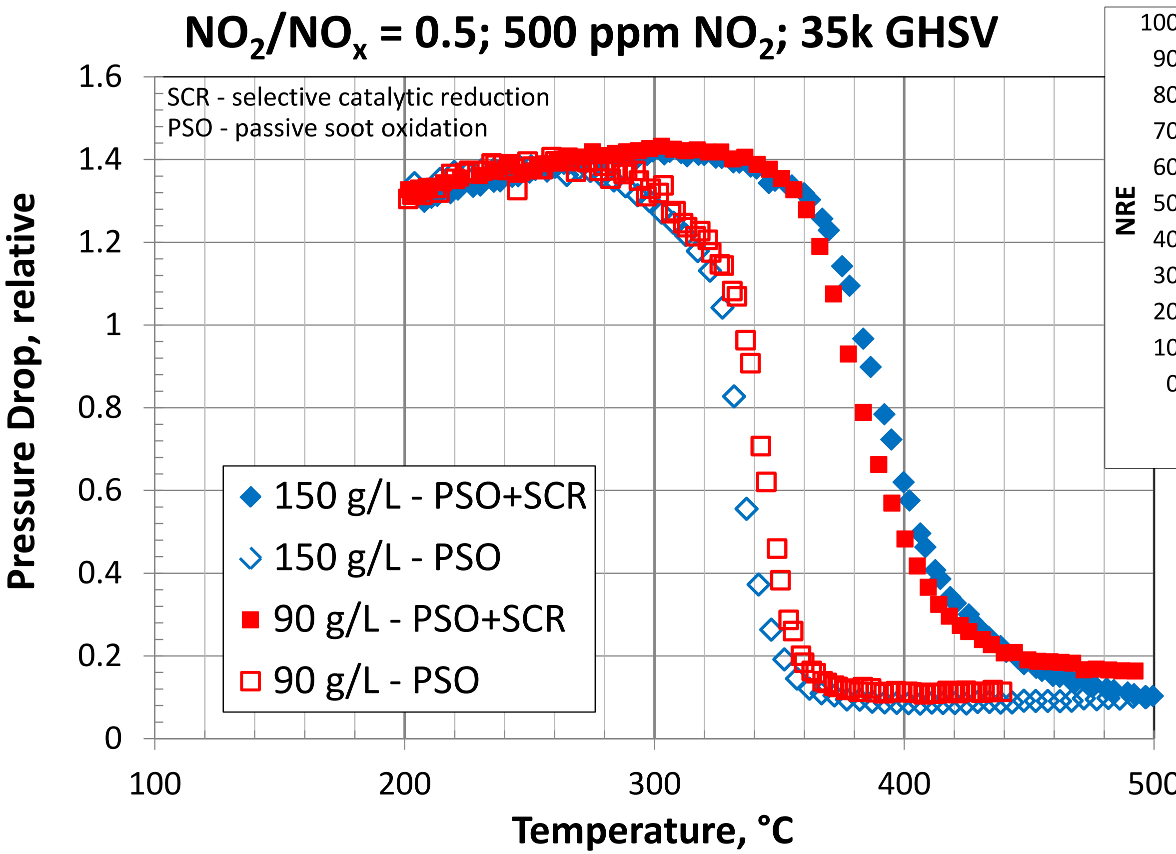


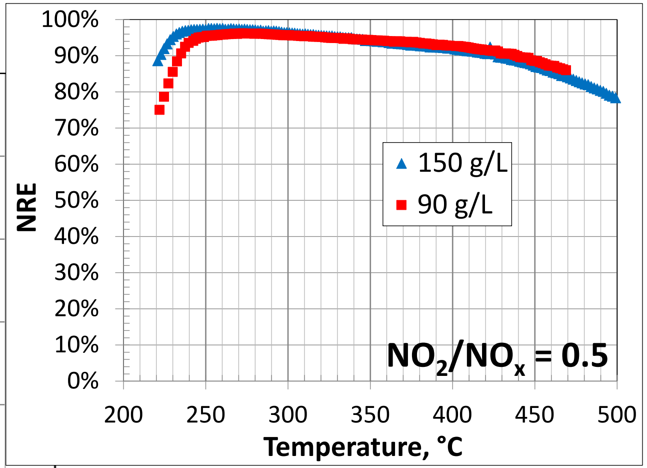


- Significantly less retardation of passive soot oxidation at NO_2/NO_x fraction >0.5

- ANR = 1
- 4 g/L soot loading

TPO – Temperature Programmed Oxidation





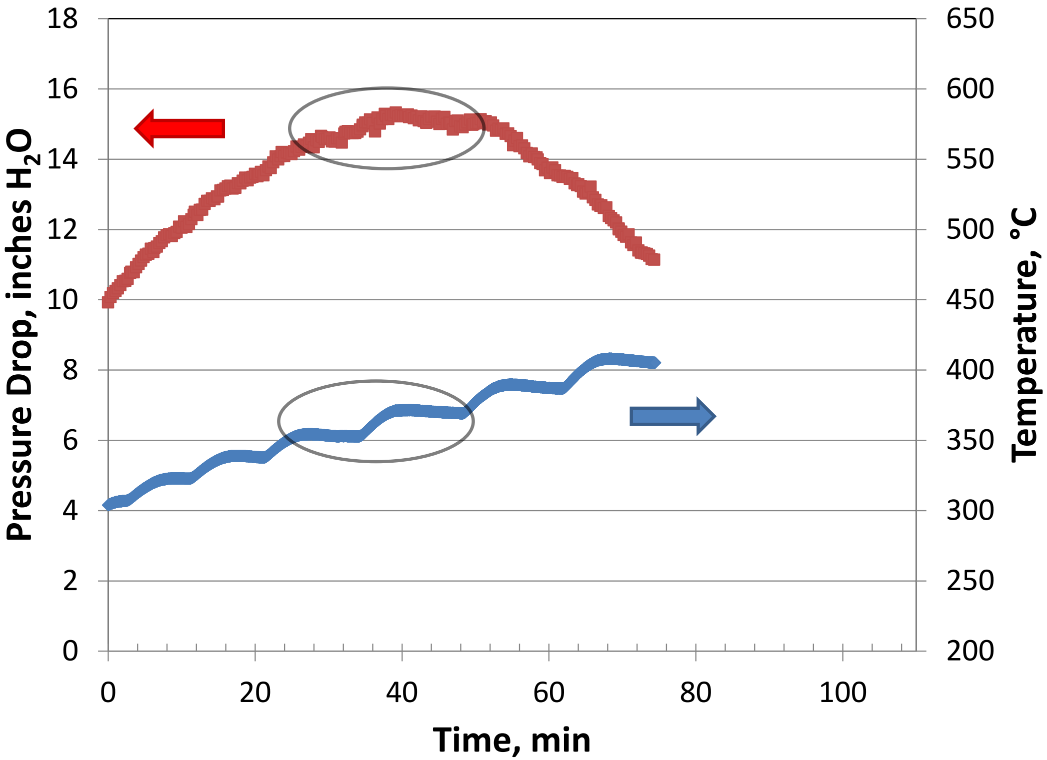
- 90 g/L SCR catalyst exhibits less retardation of PSO (~40°C) versus 150 g/L (~60°C)
- Indicates potential optimum catalyst loading target exists for facilitating PSO

- ANR = 1
- 4 g/L soot loading

TECHNICAL ACCOMPLISHMENTS

Diesel engine slipstream testing **

- Balance point temperature (BPT) analysis; 60 g/L SCR catalyst
- ANR = 0 (i.e. no SCR reaction); **BPT ~ 360°C**



300 ppm NO_x
NO_2/NO_x ~40%
~73k GHSV

Comparing to tested DAF engine + aftertreatment

High NO_x engine-out settings:
300 ppm NO_x; 40% NO_2; BPT 340–360°C

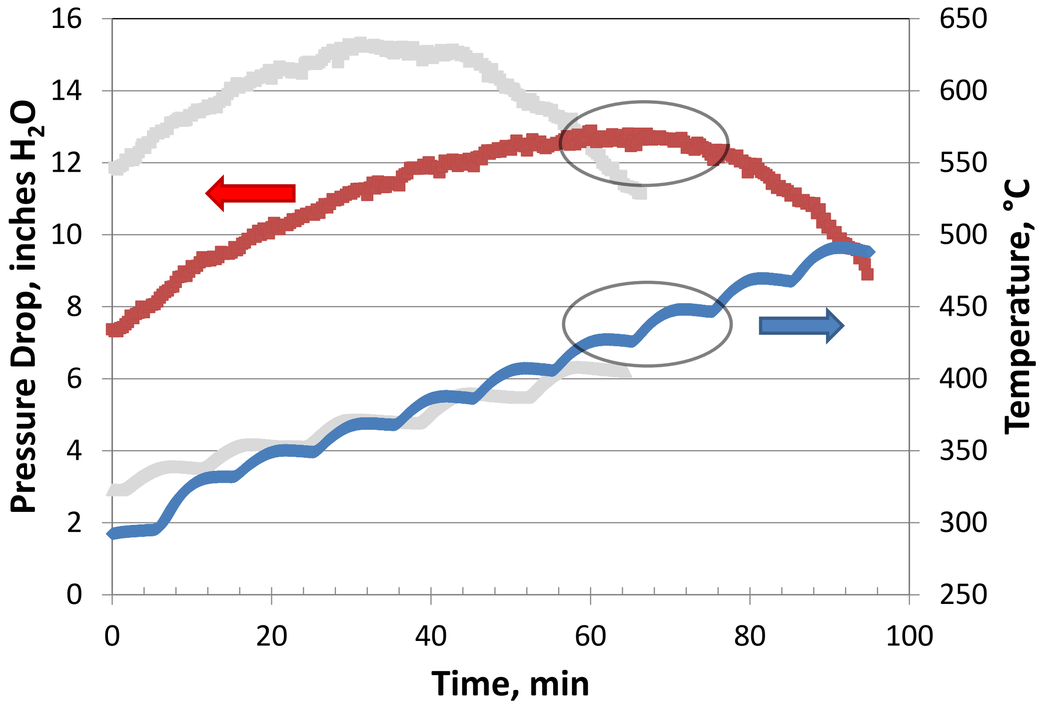
Low NO_x engine-out settings:
150 ppm NO_x; 40% NO_2; BPT 380–400 C

** See technical back-up slides for experimental configuration

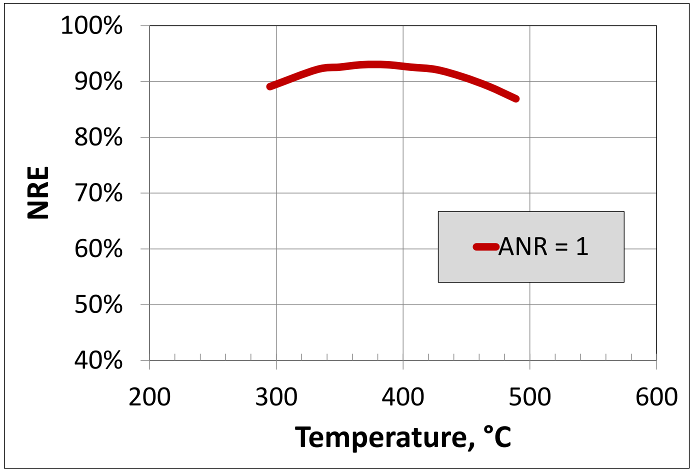
TECHNICAL ACCOMPLISHMENTS

▶ Diesel engine slipstream testing

- Balance point temperature (BPT) analysis ; 60 g/L SCR catalyst
- ANR = 1.0; BPT ~ 440°C



SCR reaction exhibits significant retarding effect on PSO process

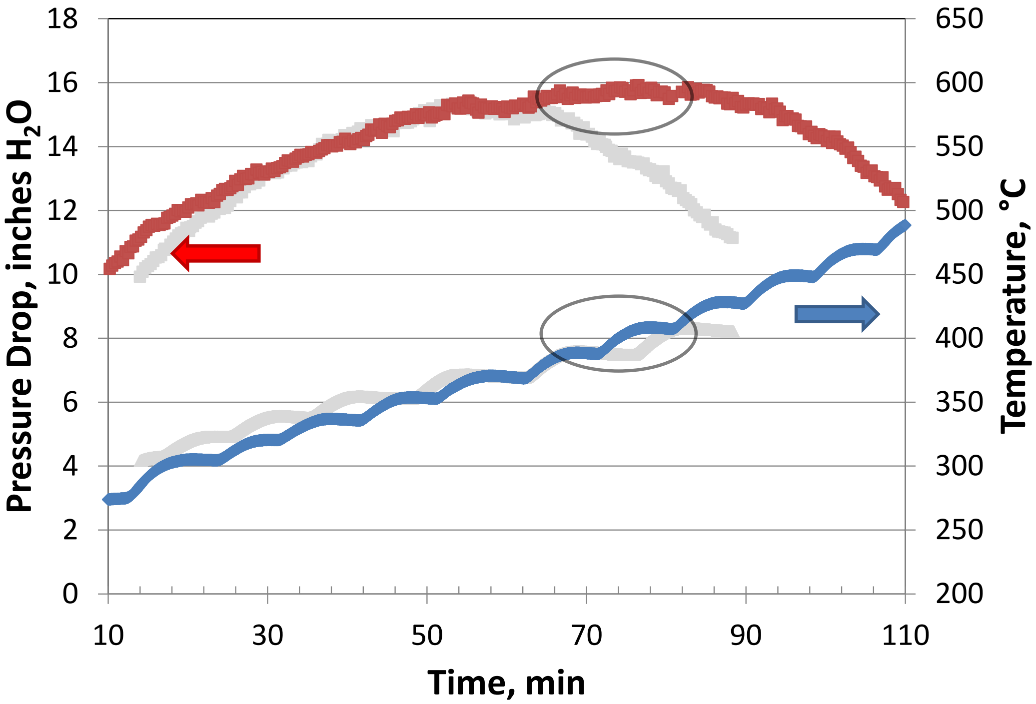


@ ANR = 1: BPT > ~80°C

TECHNICAL ACCOMPLISHMENTS

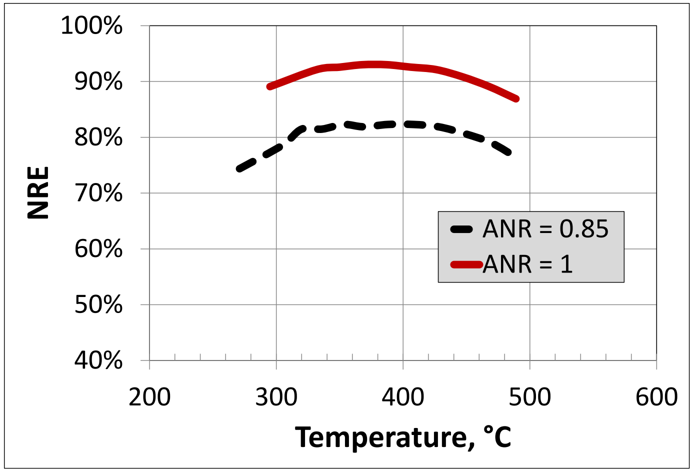
Diesel engine slipstream testing

- Balance point temperature (BPT) analysis ; 60 g/L SCR catalyst
- ANR = 0.85; BPT ~ 400°C



@ ANR = 0.85: BPT > ~40°C

Slight benefiting effect of ANR adjustment for improving PSO in presence of SCR



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COLLABORATIONS

- Partners
  - PACCAR & DAF Trucks (Industry): CRADA partner, provide engine and exhaust data used in experimental study; monthly teleconferences discussing progress and results of work
  - University of Utrecht (Academic): linking active site characteristics of developmental zeolites to deNOx activity and selectivity, characterizing deactivation phenomena; monthly teleconference participant discussing progress and results of research
  - BASF (Industry): integrated SCR/DPF parts supplier, providing wash-coating expertise and 2012 production SCR catalyst active phase
  - Corning (Industry): developmental high porosity cordierite supplier

FUTURE WORK (2012)

- Continue system kinetic and performance investigations
  - Both simulated exhaust and on engine slipstream
  - Detailed examination of SCR & PSO interactions
  - Evaluation of reductant dosing strategies for improving PSO
    - e.g. passive-active regeneration strategies
- Full-scale engine testing beginning now
  - Parts in hand, integrated with engine
  - Three configurations investigated on engine
    - Reference – typical US2010 DOC–CDPF–SCR system
    - System 1 – typical US2010 DOC + SCRF #1
    - System 2 – typical US2010 DOC + SCRF #2
    - NOTE: DOC specification can be changed based upon NO to NO_2 conversion efficiency
  - Testing consisting of the following
    - Passive & active soot oxidation under non-SCR conditions
    - Passive & active soot oxidation evaluation under SCR conditions
    - NO_x reduction efficiency of SCRF system
  - Study to include
    - Characterization after de-greening on-engine 4 hours
    - Characterization after accelerated aging at 650°C 100 hours

SUMMARY

- Impact areas
  - Optimizing SCR catalyst washcoat
  - Facilitating passive soot oxidation
- Optimizing SCR catalyst washcoat
  - Amount and location of SCR catalyst have measureable impact on dynamic permeability of filter and catalyst efficacy
  - Desired location on downstream portion of filter within porous microstructure
- Facilitating passive soot oxidation of SCR/DPF couple
  - Maximize NO_2 concentration and fraction (of total NO_x)
  - Possible optimum catalyst loading target for maximizing PSO
    - To be interrogated further on engine slip-stream configuration
  - **With catalyst optimization & passive-active regeneration strategies, definite potential for deployment of DPF/SCR system with significant passive soot oxidation capacity**

TECHNICAL BACK-UP SLIDES

- TECHNICAL BACK-UP SLIDES

RECENT FIELD OF WORK

- GM (SAE 2011-01-1140) – integrated system able to meet cert. requirements w/ significant reduction in A/T volume; coating process & ***wash-coat loading*** need optimization; approach does not address passive soot oxidation feasibility.
- JM (SAE 2011-01-1312) – addressed passive soot oxidation feasibility by turning EGR off. SCR/DPF with EGR off (elevated NO_x) demonstrated ***improved passive regeneration capability***.
- Ford (SAE 2010-01-1183) – oven aging tests indicate DOC-SCRF-SCR configuration able to meet T2B5 tailpipe NO_x standards through 120k miles.
- BASF (Boorse et al, DEER 2010) – operating window (NO_x conv., dP) ***determined by porosity, PSD***. Filter type, porosity determines catalyst utilization.

ON-ENGINE SLIPSTREAM TESTING

- Engine operated steady-state
- Catalyst temperature increased via furnace