Cummins
Sustained Low Temperature NOx Reduction (SLTNR)

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Project ID: PM068

Overview

Timeline

Start: 02/03/2015

End: 12/31/2017

Complete: 50%

Barriers

Reductant Delivery at low temperature

NOx reduction over 90% at low temperature

favorable NO_2/NOx for fast SCR reaction at low temperature

Budget

Total Project:

DoE/CMI Cost Share:$1.2M/$1.2M

PNNL funded directly by DoE: $0.6M

JMI:$0.24M

Funding received in FY 2015: $0.12M

Funding for FY 2016: $1.08M

Partners

Pacific Northwest National Lab

Johnson Matthey Inc.

Cummins Inc. (Project Lead)

Relevance and Project Objectives

Overall Objectives: Sustained Low Temperature NOx Reduction >90% at SCR inlet 150°C

- Integrated system development to approach the desirable ratio of NO and NO_2 in the SCR feed gas
- Selective catalytic reduction catalyst formulations and catalyst architectures development to achieve enhanced catalytic NOx reduction activity (>90%) at 150°C
- Robust low-temperature reductant delivery system development
- On-engine test to demonstrate the developed technical solution
- Commercial viability assessment

2015 Milestones Completed

	2015 Accomplishments	% Completion
Feb 2015	Kick-off program	100%
Jul 2015	Documented key requirements against which to assess SLTNR concepts commercial viability	100%
Oct 2015	Identified critical design parameters of SCR catalyst for low temperature fast SCR reaction	100%
Oct 2015	Reactor unit design of diesel oxidation catalysts	100%
Dec 2015	Oxidation catalyst prototype parts engine test	100%
Dec 2015	Completed assessment of reductant delivery system through paper study and lab testing	100%
Dec 2015	Go/no go review to reaffirm decision to proceed with procurement of hardware and testing of SLTNR system in 2016	100%

2016 Milestones

	2016 Milestones	% Completion
Mar 2016	Major review complete for reductant delivery system design (high risk item requires iterative generations)	100%
Mar 2016	Alpha formulation (LT SCR) prototype parts available for reactor testing	100%
May 2016	Model based design of DOC and testing completion to confirm system meets NO_2/NOx target	100%
Jun 2016	Model developed for alpha formulation LT SCR and directed the sizing of prototype system	100%
Jun 2016	Initial commercial viability analysis completed and recommendation made for prototype SLTNR system to test	90%
Jun 2016	Finalize the plan on design, hardware procurement and testing	90%
Nov 2016	Recommendation made to improve SCR catalyst formulation into beta version	50%
Dec 2016	Sub system build complete and ready for engine testing	

Technical Approach
– Enhanced Catalyst Performance With Advanced Engineering Design and Integration

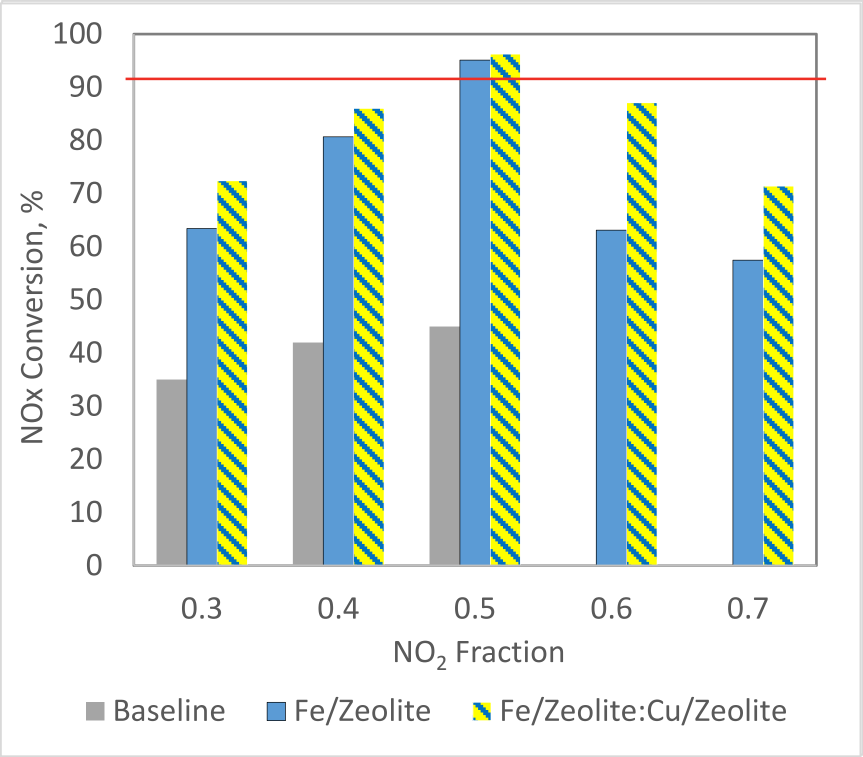
- SCR system
  - SCR formulated to minimize NH_4NO_3 formation and promote decomposition at low temperature
  - Catalyst system designed to enable fast SCR reaction with assistance of standard SCR to minimize dependence on NO_2 fraction
- DOC system
  - High performance DOC to convert HC and oxidize NO to NO_2
  - Locate DOC to minimize kinetic limitation
- Reductant Delivery System
  - Reduce droplet size to minimize residence time and temperature requirements for evaporation
- Model development to assist catalyst sizing and optimization of component/architecture design

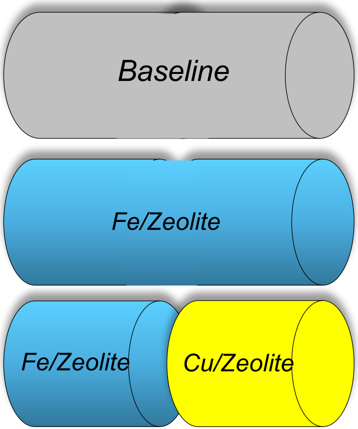
Technical Accomplishment and Progress – SCR Development

- PNNL identified critical characteristics for low temperature fast SCR performance
  - NH_4NO_3 formation is the key inhibitor
    - NH_3 storage to be minimized -> lower acid site
  - NH_4NO_3 decomposition to be promoted catalytically
    - Increase Cu/Fe sites and pore structure of zeolite
- PNNL developed a Fe/Zeolite formulation that can achieve over 90% NOx conversion at 150°C with NO_2/NOx 0.5 under lab conditions
- Johnson Matthey successfully scaled it up to monolith sample with lab-confirmed performance
- Fe/Zeolite followed by Cu/Zeolite can minimize the dependence on NO_2/NOx; optimization of Fe/Cu SCR system via model analysis and experimental test by Cummins and PNNL

Technical Accomplishment and Progress – SCR Development

Lab testing with powder at GHSV 100,000h^{-1}, 150^{o}C





Technical Accomplishment and Progress – SCR Preliminary Model Based Design

Effect of Space Velocity, NO_2/NOx on Overall Conversion Efficiency

(Fe/Zeolite SV =300K)

Assumption:

1. GHSV for monolith is 75K, which is about 25% that of Fe/Zeolite powder at loose bulk density 0.32g/cm3
2. 1D model, based on one channel

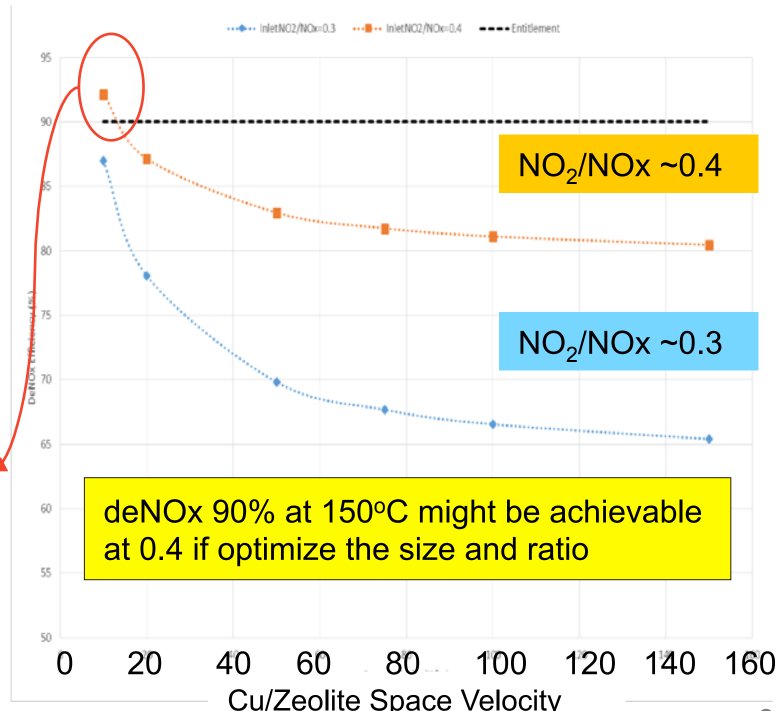
Outcome:

In this case study,

Cu/Zeolite ~5.66x9 (3.8L)

Fe/Zeolite~5.66x0.5 (0.2L)

1. It indicates Cu/Zeolite need to be sized 7~8 times of Fe/Zeolite to hit target at NO_2 frac 0.4
2. Increase Fe/Zeolite will help at NO_2 frac 0.5 but may be less beneficial to lower NO_2 fraction

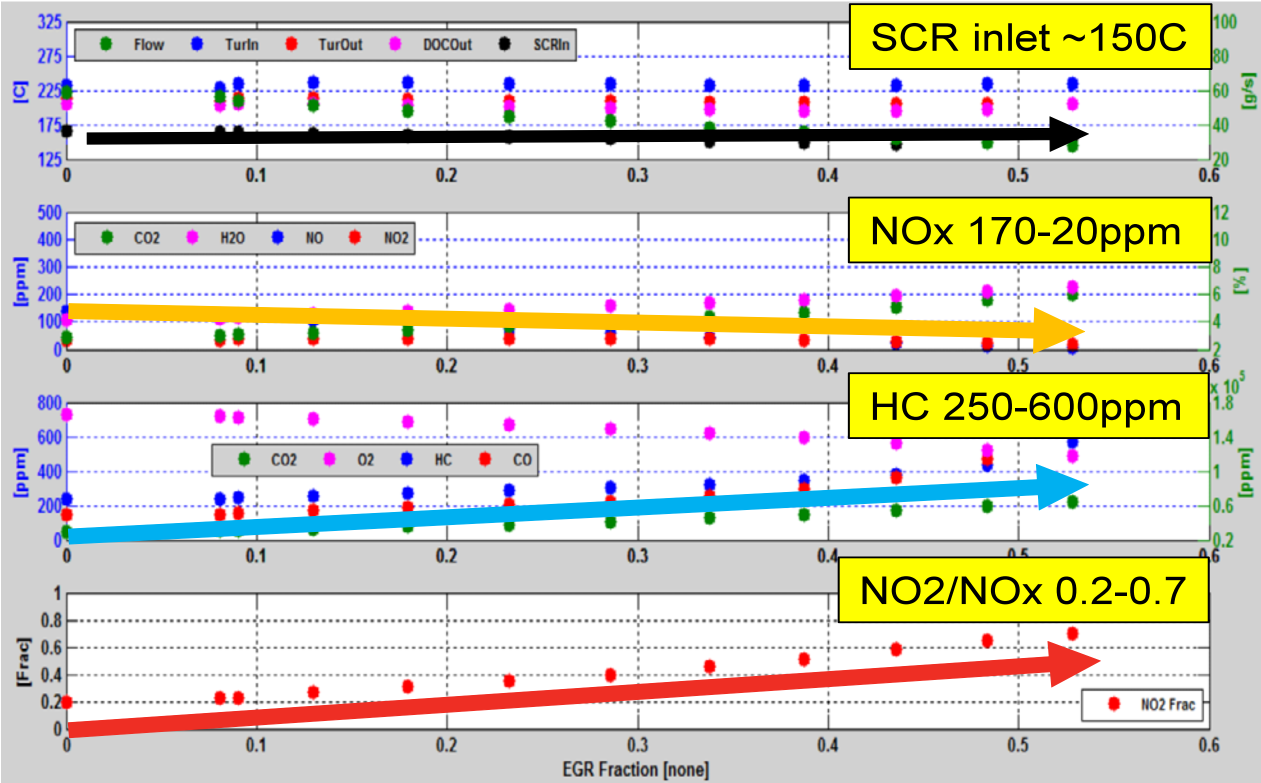


Technical Accomplishment and Progres – Integrated High NO_2 Strategy

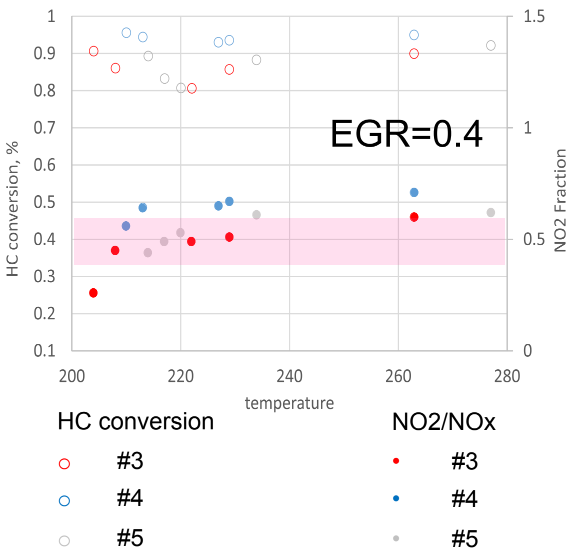
- HC is identified to be the key inhibitor for NO oxidation reaction at low operation temperature
- HC and NO_2 from engine are dependent on EGR fraction which need to be optimized to maximize DOC performance
- Johnson Matthey conducted model based design of DOC formulation and developed a DOC system with promising NO_2/NOx at low temperature operation condition
- Cummins designed a “Proof-of-Concept” DOC architecture and developed GT powder model to understand impact on engine

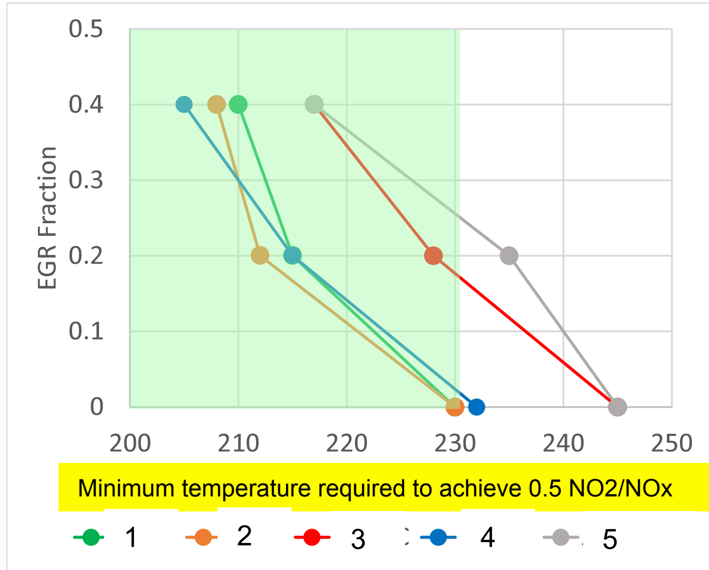
Technical Accomplishment and Progress – Integrated High NO2 Strategy

- *EGR fraction sweep*



Technical Accomplishment and Progress – Integrated High NO_2 Strategy





ID	PGM	Volume	EGR
1	Mid	High	Any
2	High	High	Any
3	Mid	Low	>0.2
4	High	Low	>0
5	Low	Mid	Close to 0.4

Technical Accomplishment and Progress – Integrated High NO_2 Strategy

Proof of Concept Design

Limited Space for Catalyst

On going: Design optimization to ensure uniform flow distribution

Next steps:

Fabrication and insulation

Engine test

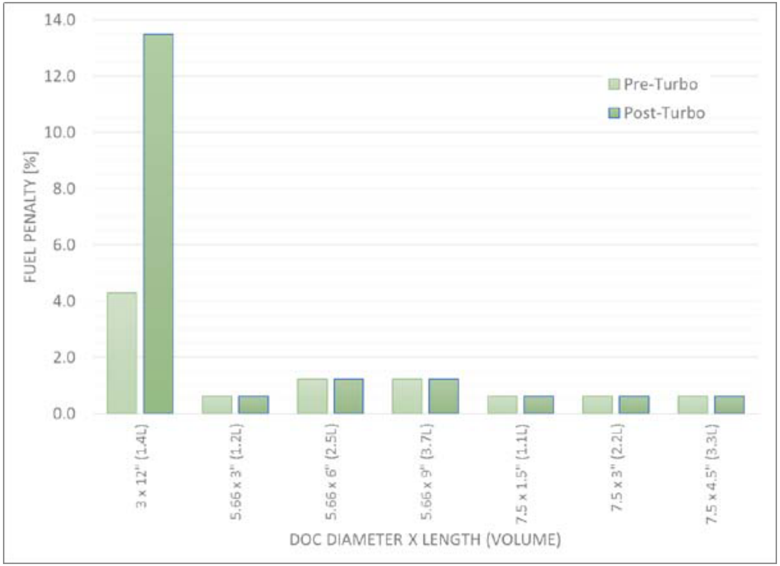
Technical Accomplishment and Progress – **Analysis Lead Design**

Utilizing GT-Power model to study impact on engine

- Simulation study underway to measure the impact of a pre-turbo catalyst on engine performance.
- A 2013 ISB (260 hp) was selected for the simulation study.
- Simulation run at 4 engine conditions
  - 2400 rpm / 570 ft-lb (rated)
  - 1600 rpm / 100 ft-lb (High Flow 200C turbine out temp)
  - 1200 rpm / 100 ft-lb (Moderate Flow 200C turbine out temp)
  - 900 rpm / 100 ft-lb (Low Flow 200C turbine out temp)
- Engine inputs kept constant & the impact of size and dimensions of the catalyst on selected parameters was studied.

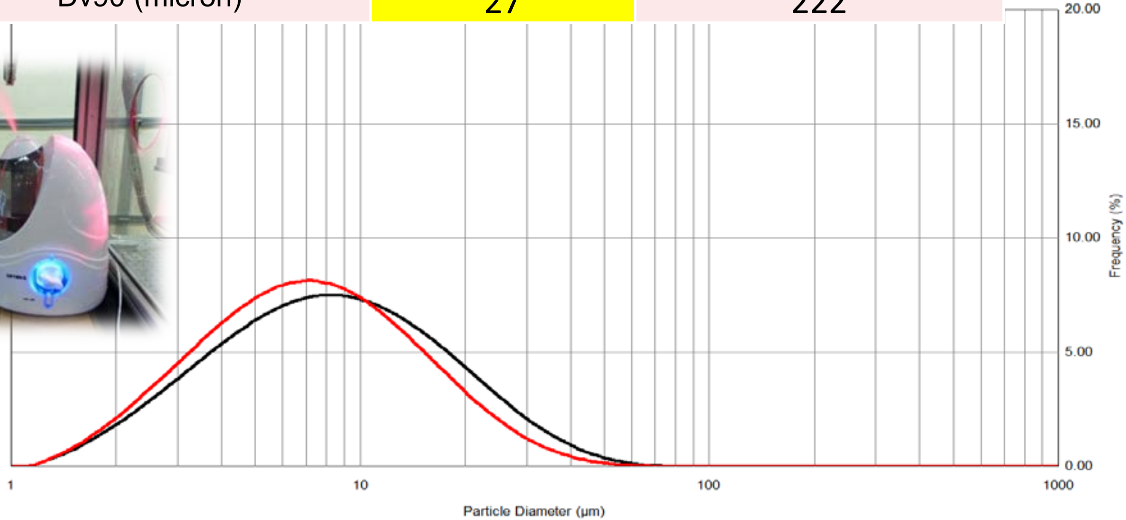
Technical Accomplishment and Progress – GT Power Simulation on Pre-Turbo Concept

- Target at least a 5.66” diameter
  - ✓ Larger is better; need to consider packaging trade-off
- Model suggests reasonable fuel penalty at this diameter
  - ✓ 0.5 – 1.5% - slight benefit at larger diameter, but poor packaging trade-off
  - ✓ Fuel economy penalty similar to locating element post turbo until diameter is very small, then some benefit to locating pre-turbo



Technical Accomplishment and Progress – Vaporizer Design Proof of Concept

Averaged Derived Parameter	Vaporizer	Bosch 2.2 A030P707
SMD (micron)	5-7	72.5
Dv90 (micron)	27	222



	Date-Time	File	Sample	Dx(10)	Dx(50)	Dx(90)
[V] (black)	Aug 5 2015-15:0...	Cl2-0mm-20mm 1 1	Cl2-0mm-20mm	2.96	8.12	21.94
[V] (red)	Aug 5 2015-15:1...	Cl2-0mm-20mm 1 1	Cl2-0mm-20mm	2.79	7.09	18.13

[V]=Volume [N]=Number

Technical Accomplishment and Progress – Vaporizer Design Proof of Concept

Averaged Derived Parameter	Vaporizer	Bosch 2.2 A030P707
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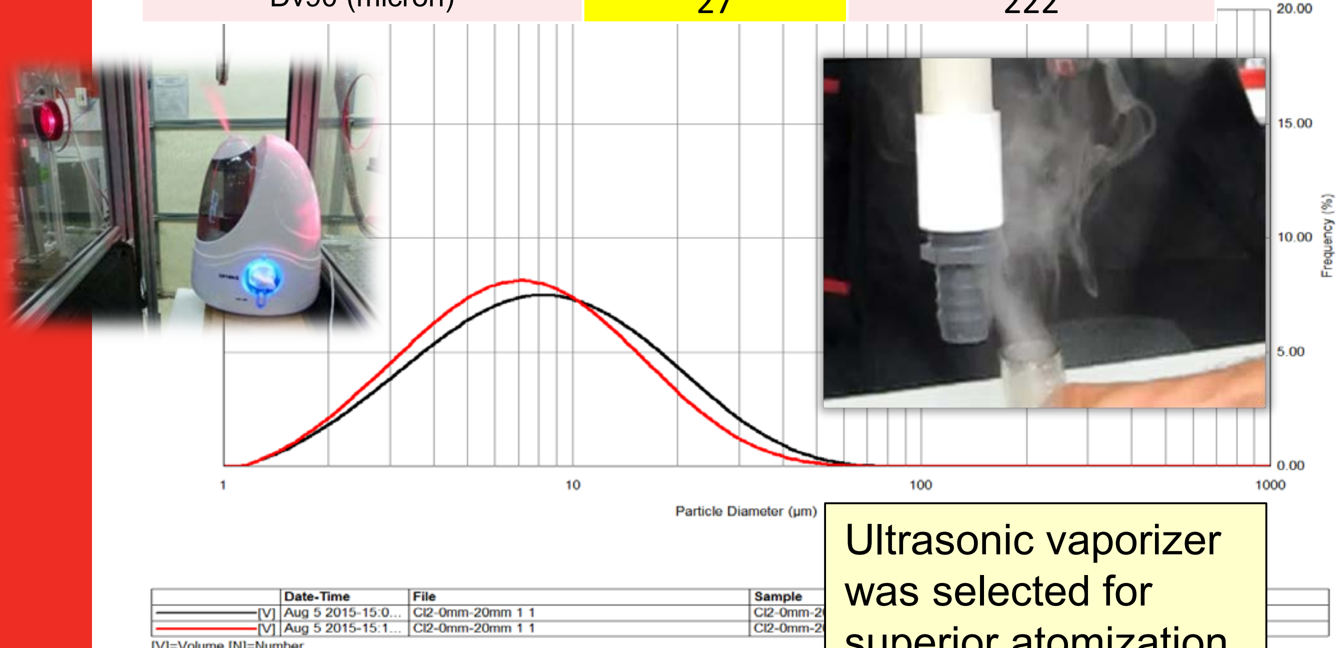

Ultrasonic vaporizer was selected for superior atomization

Technical Accomplishment and Progress –

Vaporizer Design in Process to Improve Flow Distribution…

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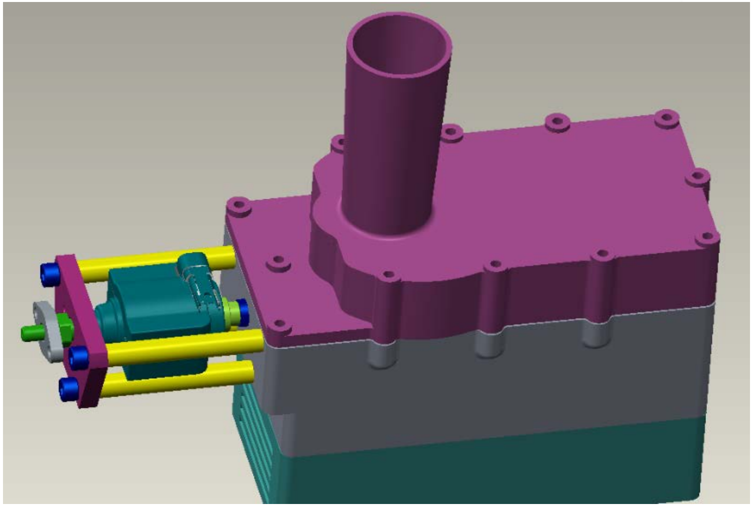
- All off-the-shelf components except for housings;
- Design optimization via Computational Fluid Dynamics (CFD) and testing iteratively for flow uniformity and pressure optimization;



- A feedforward control in development using correlations between vapor generated at a known voltage, and liquid temperature and fluid level;
- Key challenge remains in creating air pressure control algorithm for all operation conditions;
- **Prototype build in June 2016**

Technical Accomplishment and Progress – Commercial Viability Assessment

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Aspect	Evaluation Criteria / Baseline	Current Feasibility	2 Yr. Potential	4 Yr. Potential	6 Yr. Potential	8 Yr. Potential
Initial Purchase Price						
System Cost	Current cost of baseline system = 1x	Rate with a feasibility percentage utilizing baseline and anticipated system cost				
Operating Cost						
Active Regen Frequency (Reduced Passive Regeneration)	Time between active regens over operating duty cycle	Rate with a feasibility percentage utilizing baseline system values and anticipated performance of final system				
Fluid Economy over drive cycle	Fuel + Urea consumption over cold FTP + warm FTP					
Fluid Economy over low temperature operation	Fuel + Urea consumption over low temperature cycle					
Backpressure	Exhaust manifold pressure at rated temperature and flow					
Maintenance Cost						
RF1-Durability of Fe/Zeolite SCR	Hydrothermal aging comparison to Cu/Zeolite SCR	Percentage confidence in ability to develop countermeasures				
RF2- Durability of Pre-turbo Catalyst	Hydrothermal aging of DOC at elevated temperature					
RF3- Durability of engine system with Pre-turbo Catalyst	Assessment of DOC debris, impact on engine life					
RF4-Robustness of DOC to maintain 0.5 NO2/Nox ratio	Assessment of aging impact					
RF5 -Durability /Useful Life of Urea Vaporizer	Assess lifetime compared to current urea dosing system					
OEM Development Cost						
Packaging Impact to Vehicle	Baseline engine/aftertreatment space claim envelope	Percentage confidence in ability to develop countermeasures				
Estimated System Feasbility		Multiply rows to develop overall estimated confidence measure				

Current Identified Risk Factors (RF)

RF1-Durability of Fe/Zeolite SCR	Hydrothermal aging comparison to Cu/Zeolite SCR
RF2- Durability of Pre-turbo Catalyst	Hydrothermal aging of DOC at elevated temperature
RF3- Durability of engine system with Pre-turbo Catalyst	Assessment of DOC debris, impact on engine life
RF4-Robustness of DOC to maintain 0.5 NO2/Nox ratio	Assessment of aging impact
RF5 -Durability /Useful Life of Urea Vaporizer	Assess lifetime compared to current urea dosing system

Judge feasibility as a percentage compared against baseline system or as confidence in managing identified risks

Roll up confidence measure to provide indication of potential for final system

Summary -

- A DOC system is developed with a favorable NO_2/NOx at targeted operation conditions
- The new formulated Fe/Zeolite model catalyst can achieve > 90% of NOx conversion at steady state 150°C of SCR inlet with ideal lab condition: NO_2/NOx 0.5, ANR1 and no HC in feed gas. A hybrid SCR design with Fe/Zeolite followed by Cu/Zeolite can reduce the sensitivity to NO_2/NOx and might achieve target with lower NO_2 /NOx (e.g.0.4)
- Ultrasonic vaporizer can facilitate the reduction of droplet size to minimize residence time of DEF droplet at low temperature. The main challenges remain on system integration

Collaboration Partners

- **Department of Energy**
- **Cummins, Inc.**
- **Pacific Northwest National Laboratory**
- **Johnson Matthey, Inc.**

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JM Johnson Matthey

CMI leads the SLTNR program with the focus on system integration, model simulation, on-engine demo and commercial viability assessment, including NH3 delivery system, DOC system, and SCR system

PNNL supports SCR development to carry out fundamental studies on critical catalyst features needed to enhance LT SCR performance; and to make recommendations on formulations

JMI provides development and application support of aftertreatment catalysts, including powder, core and full size prototypes. JMI also provides aftertreatment modeling support. JMI commercial DOC and SCR catalyst as baseline

Remaining Challenge

- Catalyst
  - Durability and Robustness of performance at all operation conditions
- Urea Vaporizer
  - Technology concept feasibility and capability
  - Durability and useful life

Future Work

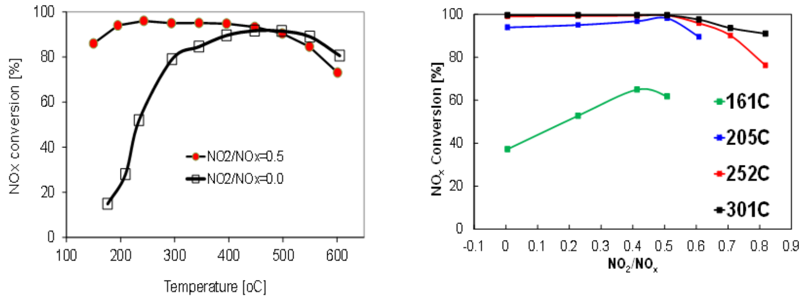
- Integrated High NO_2 strategy
  - 2016: Complete DOC architecture proof of concept design for engine test
  - 2016: Work with JM to optimize DOC formulation and size via model simulation, experimental and engine test
  - 2016: Exhaust manifold re-design
- SCR System
  - 2016: Work with JM to scale up Fe/Zeolite 1st Gen for engine test
  - 2016: Hybrid SCR system optimization (ratio/size) via model simulation, experimental and engine test
  - 2016: Work with PNNL and JM to optimize Fe/Zeolite for 2nd Gen
- Reductant Delivery System
  - 2016: Complete proof of concept design, CFD analysis, prototype build and bench testing
  - 2016: System integration and control
  - 2016: Engine test

Technical Backup

Technical Accomplishment and Progress – SCR Development

- ***Objective:*** *Sustained 90% conversion of NOx emissions entering the SCR catalyst at 150 °C*
- ***Baseline:***

State-of-the-art Catalysts of 2010, studied by Cummins



Fe/zeolite

Cu/zeolite

NOx conversion dependency of Fe-zeolite and Cu-zeolite catalysts on reaction temperature and sensitivity to NO_2/NOx ratio at low temperatures. Parts treated at 600°C 2h; NO=200 ppm, ANR = 1, SV=40K.

- ***Statement of Challenge:*** NH_4NO_3 formation
- ***Design Path***

1) Prevent NH_4NO_3 formation at 150 °C
2) Promote removal of deposited NH_4NO_3 at 150 °C

Technical Accomplishment and Progress – SCR Development

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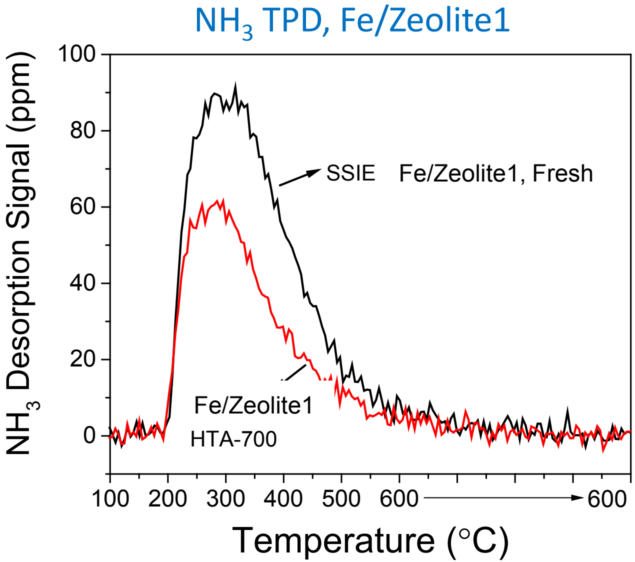
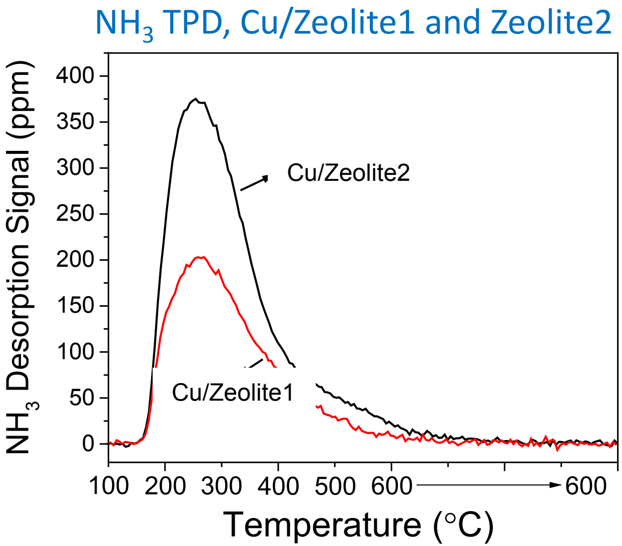


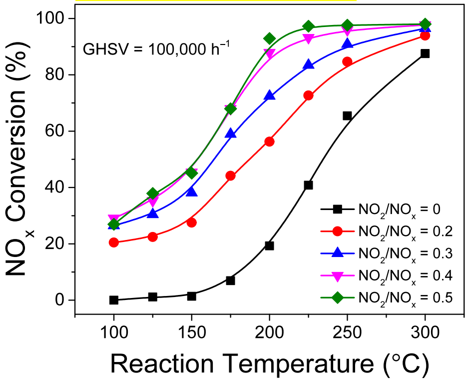


- When HTA Fe/Zeolite1 and Cu/Zeolite1 are compared, NH_3 storage capacity for Fe/Zeolite1 is only 30% of that for Cu/Zeolite1.
- Much lower NH_4NO_3 formation rate. No net accumulation at 150 °C.

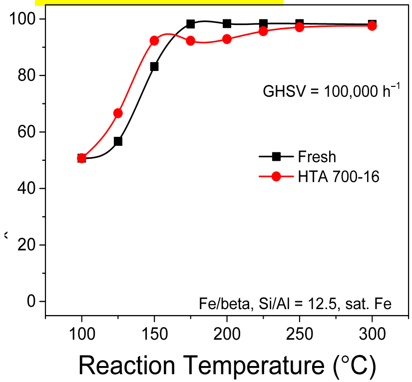
F. Gao, Y. Wang, M. Kollár, N. M. Washton, J. Szanyi, C. H.F. Peden, *Catalysis Today*, in press. DOI:10.1016/j.cattod.2015.01.025.

Technical Accomplishment and Progress – PNNL SCR Formulation Development

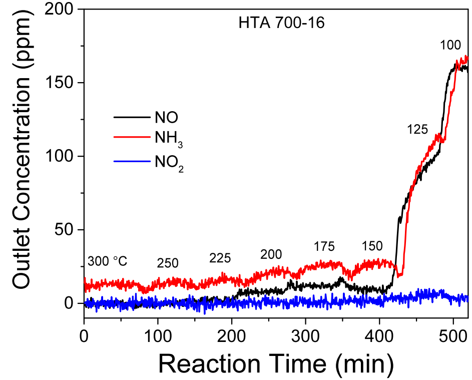
Baseline Fe/Zeolite



PNNL Fe/Zeolite



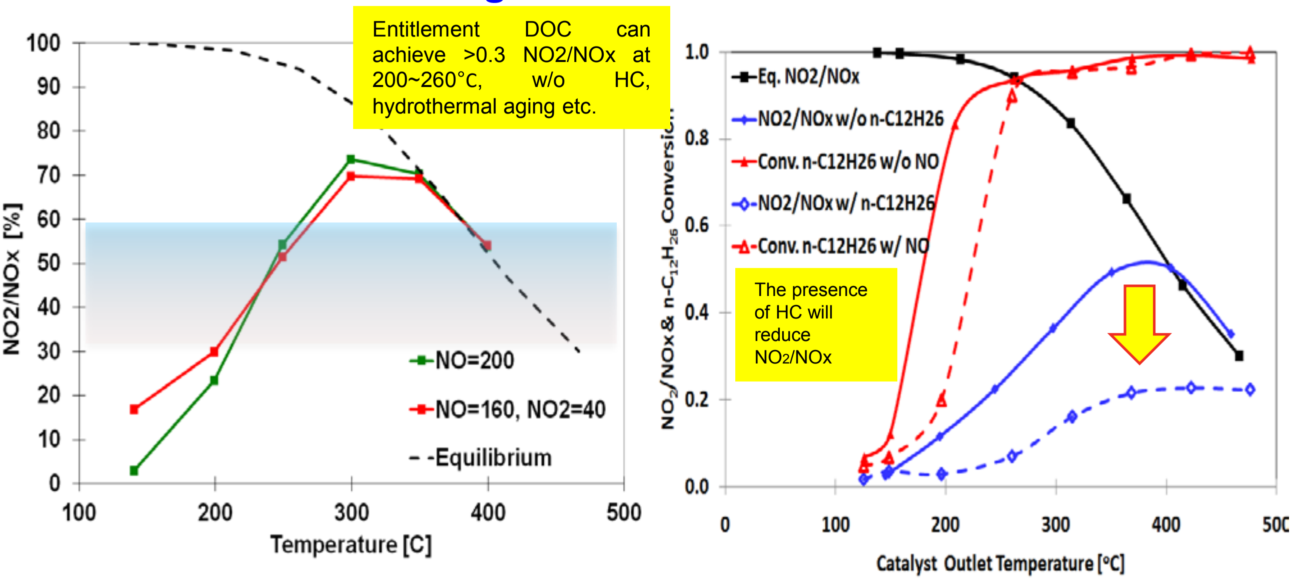
PNNL Fe/Zeolite



- Over 90% NOx conversion at 150 °C on the HTA-700 sample under **steady-state**. No accumulation of NH_4NO_3 observed at this temperature.
- For Fe/Zeolite, hydrothermal aging indeed causes considerable NOx conversion increase at 150 °C.

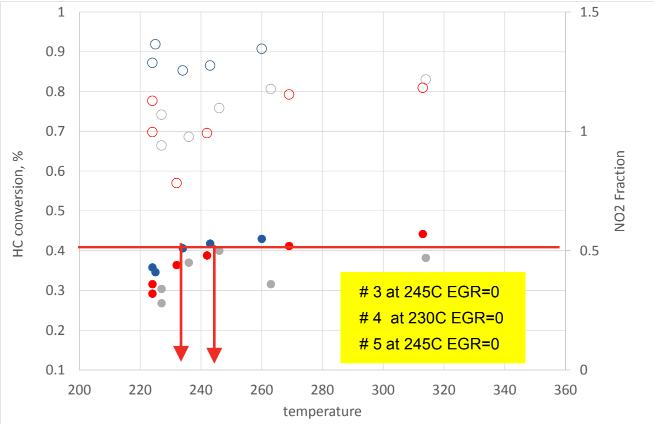
Technical Accomplishment and Progress – DOC System Development

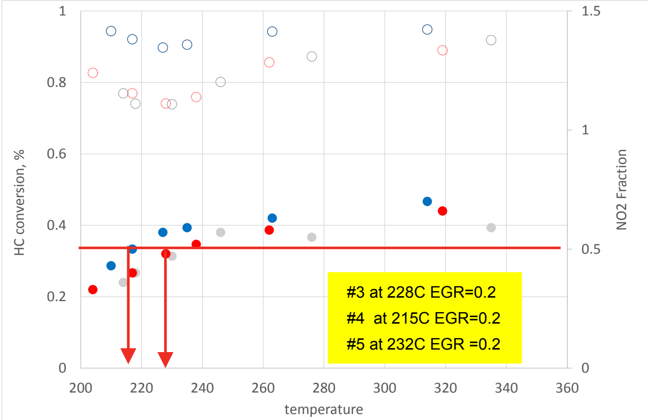
- ***Objectives:*** deliver favorable NO2/NOx fraction to SCR at low temperature operation condition
- ***Statement of Challenge:*** Kinetic limitation and HC inhibition

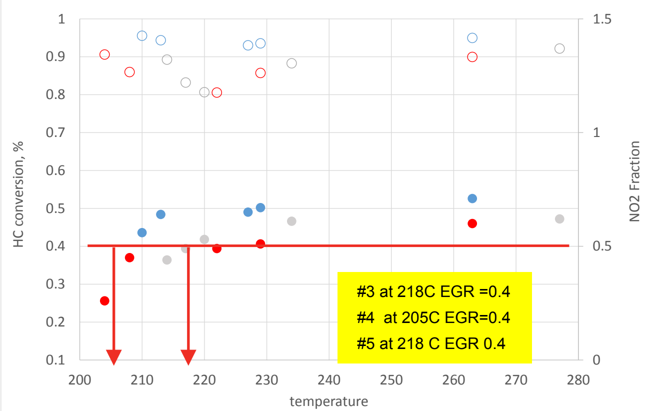


- ***Design Concept:*** 1) DOC optimization with HC control and NO2 generation; 2) Locate DOC at high temperature zone of aftertreatment

Technical Accomplishment and Progress – Integrated High NO_2 Strategy







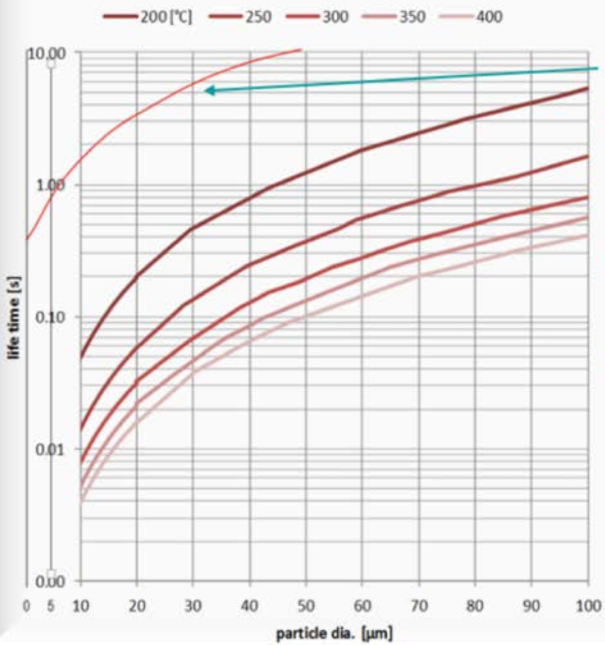
HC conversion		NO2/NOx	
○	#3	•	#3
○	#4	•	#4
○	#5	•	#5

- Increase of HC conversion promotes NO oxidation
- NO oxidation performance is sensitive to temperature

Technical Accomplishment and Progress – Reductant Delivery System

- ***Objective*** : deliver reductant under sustained operation at SCR inlet 150°C
- ***Statement of Challenge***:
- ***Design Concept***
  - Reduce droplets Size :Ultrasonic vaporizer

Residence Time vs Droplet Size



- Extrapolated curve at 150C
- Data for droplets < 20 µm has also been extrapolated from existing Lundström chart.
- At ultrasonic SMD of 5-7 µm, approx. residence time is .8 sec.
- Full disassociation of water may not be necessary, and may also depend on humidity of exhaust gas.

Lundström, Andreas, Henrik Ström, and Magnus Skoglundh. "Dispersion Aspects of NH3-Delivery Strategies for NH3-Based SCR Systems." Topics in Catalysis (2013): 1-5.