Cummins
Sustained Low Temperature NOx Reduction (SLTNR)

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June 9, 2016

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Overview

Timeline
Start: 02/03/2015
End: 12/31/2017
Complete: 50%

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

Barriers
Reductant Delivery at low temperature
NOx reduction over 90% at low temperature
favorable NO₂/NOx for fast SCR reaction at low temperature

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 NO₂ 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

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## 2015 Milestones Completed

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

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone</th>
<th>Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 2016</td>
<td>Major review complete for reductant delivery system design (high risk item requires iterative generations)</td>
<td>100%</td>
</tr>
<tr>
<td>Mar 2016</td>
<td>Alpha formulation (LT SCR) prototype parts available for reactor testing</td>
<td>100%</td>
</tr>
<tr>
<td>May 2016</td>
<td>Model based design of DOC and testing completion to confirm system meets NO$_2$/NOx target</td>
<td>100%</td>
</tr>
<tr>
<td>Jun 2016</td>
<td>Model developed for alpha formulation LT SCR and directed the sizing of prototype system</td>
<td>100%</td>
</tr>
<tr>
<td>Jun 2016</td>
<td>Initial commercial viability analysis completed and recommendation made for prototype SLTNR system to test</td>
<td>90%</td>
</tr>
<tr>
<td>Jun 2016</td>
<td>Finalize the plan on design, hardware procurement and testing</td>
<td>90%</td>
</tr>
<tr>
<td>Nov 2016</td>
<td>Recommendation made to improve SCR catalyst formulation into beta version</td>
<td>50%</td>
</tr>
<tr>
<td>Dec 2016</td>
<td>Sub system build complete and ready for engine testing</td>
<td></td>
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</tbody>
</table>
Technical Approach

– Enhanced Catalyst Performance With Advanced Engineering Design and Integration

- **SCR system**
  - SCR formulated to minimize NH$_4$NO$_3$ 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
  - NH₄NO₃ formation is the key inhibitor
    - NH₃ storage to be minimized -> lower acid site
  - NH₄NO₃ 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 NO₂/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 NO₂/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 100,000 h⁻¹, 150°C

![Bar chart showing NOx Conversion vs NO₂ Fraction for Baseline, Fe/Zeolite, and Fe/Zeolite:Cu/Zeolite conditions.]

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Technical Accomplishment and Progress – SCR Preliminary Model Based Design

Effect of Space Velocity, NO2/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 NO₂ frac 0.4
2. Increase Fe/Zeolite will help at NO₂ frac 0.5 but may be less beneficial to lower NO₂ fraction

NO₂/NOx ~0.4
NO₂/NOx ~0.3

denoX 90% at 150°C might be achievable at 0.4 if optimize the size and ratio
Technical Accomplishment and Progress
– Integrated High NO₂ Strategy

- HC is identified to be the key inhibitor for NO oxidation reaction at low operation temperature
- HC and NO₂ 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 NO₂/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

- SCR inlet ~150°C
- NOx 170-20ppm
- HC 250-600ppm
- NO₂/NOx 0.2-0.7

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Technical Accomplishment and Progress – Integrated High NO₂ Strategy

EGR=0.4

Minimum temperature required to achieve 0.5 NO₂/NOx

<table>
<thead>
<tr>
<th>ID</th>
<th>PGM</th>
<th>Volume</th>
<th>EGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mid</td>
<td>High</td>
<td>Any</td>
</tr>
<tr>
<td>2</td>
<td>High</td>
<td>High</td>
<td>Any</td>
</tr>
<tr>
<td>3</td>
<td>Mid</td>
<td>Low</td>
<td>&gt;0.2</td>
</tr>
<tr>
<td>4</td>
<td>High</td>
<td>Low</td>
<td>&gt;0</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>Mid</td>
<td>Close to 0.4</td>
</tr>
</tbody>
</table>
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

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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.
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

<table>
<thead>
<tr>
<th>Averaged Derived Parameter</th>
<th>Vaporizer</th>
<th>Bosch 2.2 A030P707</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMD (micron)</td>
<td>5-7</td>
<td>72.5</td>
</tr>
<tr>
<td>Dv90 (micron)</td>
<td>27</td>
<td>222</td>
</tr>
</tbody>
</table>

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Ultrasonic vaporizer was selected for superior atomization.
Technical Accomplishment and Progress –
Vaporizer Design in Process to Improve Flow Distribution

- 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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### Current Identified Risk Factors (RF)

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

### 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.

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 NO₂ 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

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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

![Graph showing NOx conversion dependency of Fe-zeolite and Cu-zeolite catalysts on reaction temperature and sensitivity to NO2/NOx ratio at low temperatures. Parts treated at 600°C 2h; NO=200 ppm, ANR = 1, SV=40K.]

- **Statement of Challenge:** NH4NO3 formation

- **Design Path**
  1) Prevent NH4NO3 formation at 150 °C
  2) Promote removal of deposited NH4NO3 at 150 °C
When HTA Fe/Zeolite1 and Cu/Zeolite1 are compared, NH₃ storage capacity for Fe/Zeolite1 is only 30% of that for Cu/Zeolite1.

Much lower NH₄NO₃ formation rate. No net accumulation at 150 °C.

Over 90% NOx conversion at 150 °C on the HTA-700 sample under **steady-state**. No accumulation of NH₄NO₃ 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 NO\textsubscript{2}/NO\textsubscript{x} 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 NO\textsubscript{2} generation; 2) Locate DOC at high temperature zone of aftertreatment
Technical Accomplishment and Progress – Integrated High NO₂ Strategy

- 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

- **Design Concept**

- **Statement of Challenge**: Reduce droplets Size: Ultrasonic vaporizer

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*Residence Time vs Droplet Size*

- Extrapolated curve at 150°C
- 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.

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