SUSTAINED LOW TEMPERATURE NOX REDUCTION (SLTNR)

Yuhui Zha, Principal Investigator

Michael Cunningham, John Heichelbech, Venkata Lakkireddy, Ashok Kumar, Anand Srinivasan, Jinyong Luo, and Aleksey Yezerets

Feng Gao, Janos Szanyi, Yong Wang, and Yang Zheng

Zhehao Wei, Howard Hess, Haiying Chen, Joseph Fedeyko and Balaji Sukumar

Co-funded by

SLTNR Initiatives

Current Application Challenge	Near Term Application Challenge	Long Term Application Challenge
• Gaps between regulatory cycle and low load real world operations • Inherent challenges in catalysts, reductant delivery system and sensors	• Gains in fuel efficiency are translating into substantial exhaust temperature reduction	• Further fuel efficiency improvements are underway. • CARB intends to adopt 0.02g/bhp.hr NOx standard in 2023

System Solution Challenge

- Cold start
- Sustained low temperature

Chemical and Engineering Challenge

- SCR self-inhibition by NH4NO3
- Unfavorable NO_2/NOx
- DEF deposit

Cooperative Partners

Department of Energy

Cummins, Inc.

Pacific Northwest National Laboratory

Johnson Matthey, Inc.

SLTNR Objectives

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

Develop **SCR catalyst** that enables sustained 90% conversion of NOx entering the SCR catalyst at 150°C

Develop an integrated system capable of providing needed **NO_2/NOx** ratio at SCR inlet 150°C

Develop an appropriate means to robustly **deliver reductant** under sustained operation at SCR inlet 150°C

Develop a model to assess the **commercial viability** of the proposed SLTNR system and **on-engine demonstration** of the developed prototype system

Acknowledgement

- ***Vehicle Technologies Office, Department of Energy:*** Jerry Gibbs
- ***National Energy Technology Laboratory:*** Walter (Jerry) Parker

- ***"DeNOx" research team at Pacific Northwest National Lab:*** Feng Gao, Márton Kollár, Yilin Wang, János Szanyi, Chuck Peden, George Muntean, Mark Stewart, Yong Wang

- ***Catalyst support team at Johnson Matthey:*** Howard Hess, Hai-ying Chen, Zhehao Wei, Joseph Fedeyko, Sampling Team, Balaji Sukumar

- ***Integration support at Cummins :*** Aleksey Yezerets, Michael Cunningham, John Heichelbech, Neal Currier, Krishna Kamasamudram, Ashok Kumar, John Luo, Venkata Lakkireddy, Anand Srinivasan, Saurabh Joshi, Yadan Tang, Tyler Rash, Matt Anderson, Johnny Cai, John Henderson, Enoch Nanduru, Vinay Joshi, Samuel Johnson, John Buechler, Rei Tangko
- ***Test Cell Support***: Analytical Engineering, Inc.
- ***Design&Fabrication:*** Cole Tech

Key Accomplishments

A Developed SCR formulation to achieve 90% NOx reduction target at 150°C with favorable range of NO_2/NOx in feed gas;

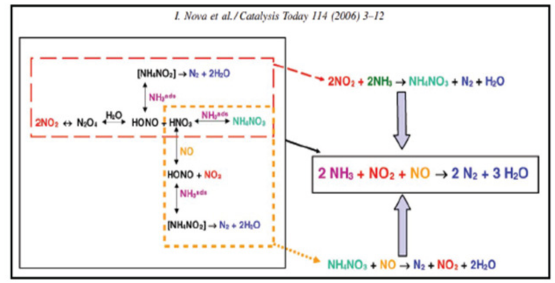
B Developed DOC formulation and architecture concepts to achieve favorable NO_2/NOx in feed gas of SCR at 150 °C;

C Developing reductant vaporizer technology to reduce droplet size and therefore minimize requirements of temperature and residence time

A SCR Component and System Development Path

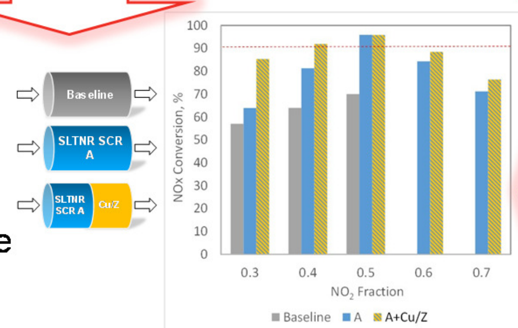
Challenges Identified For Low Temperature SCR

SCR at low temperature proceeds predominantly through the mechanism involving formation, sublimation and decomposition of AN; Self-inhibition due to AN accumulation is the key barrier for best-in-class Cu-SCR at low temp;

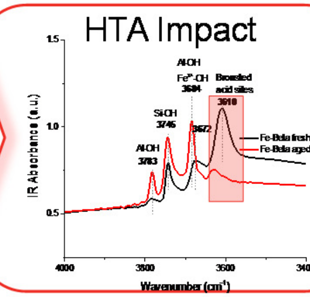


Development and optimization of formulation

PNNL/JM developed SLTNR SCR A and B with minimal NH4NO3 formation; SLTNR SCR followed by Cu/Z hybrid system proved promising for broader range of temperature inlet NO2/NOx ratio; on-going fundamental study on robustness and durability



Lab Diagnostics



Scale-up from powder to monolith by JM

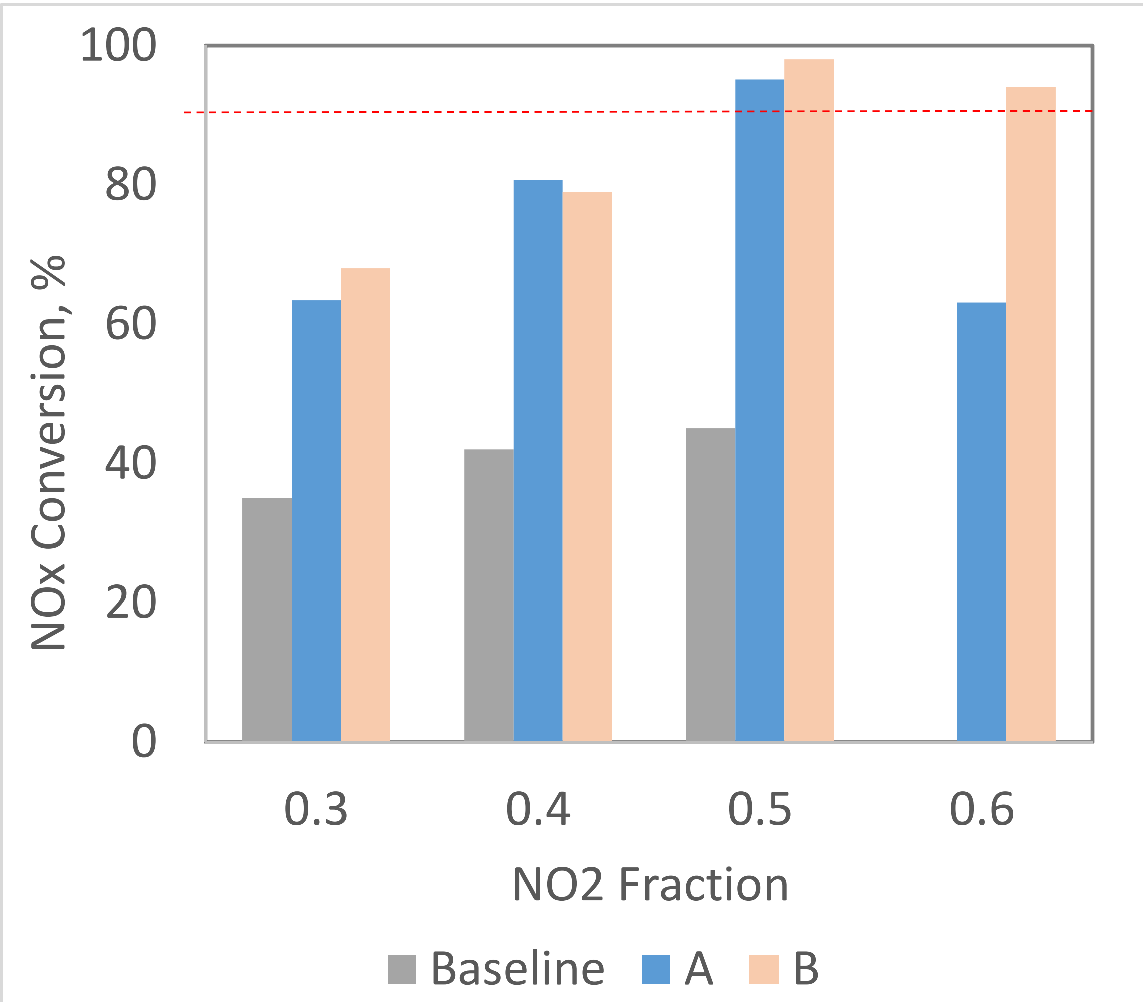
Model to support system performance evaluation

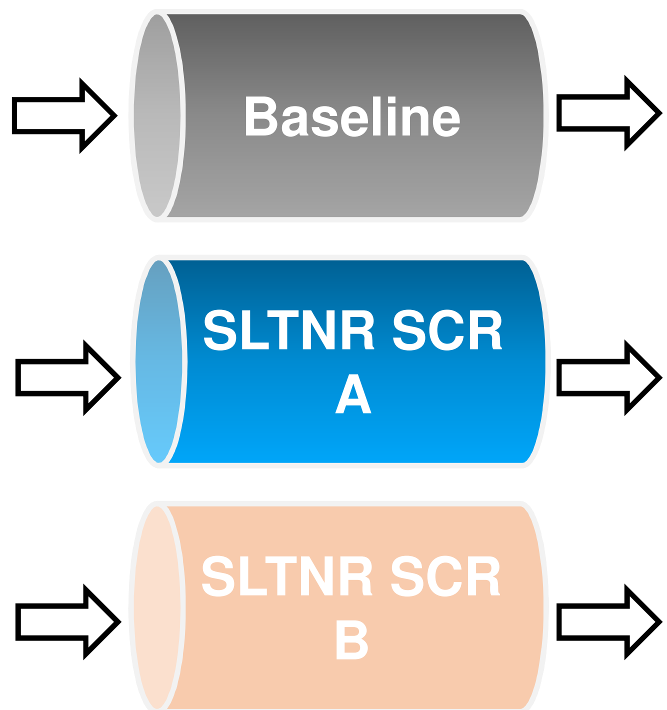
Engine Demo to quantify application potentials and gaps

Commercial Assessment

Ⓐ Low Temperature SCR Formulation Development

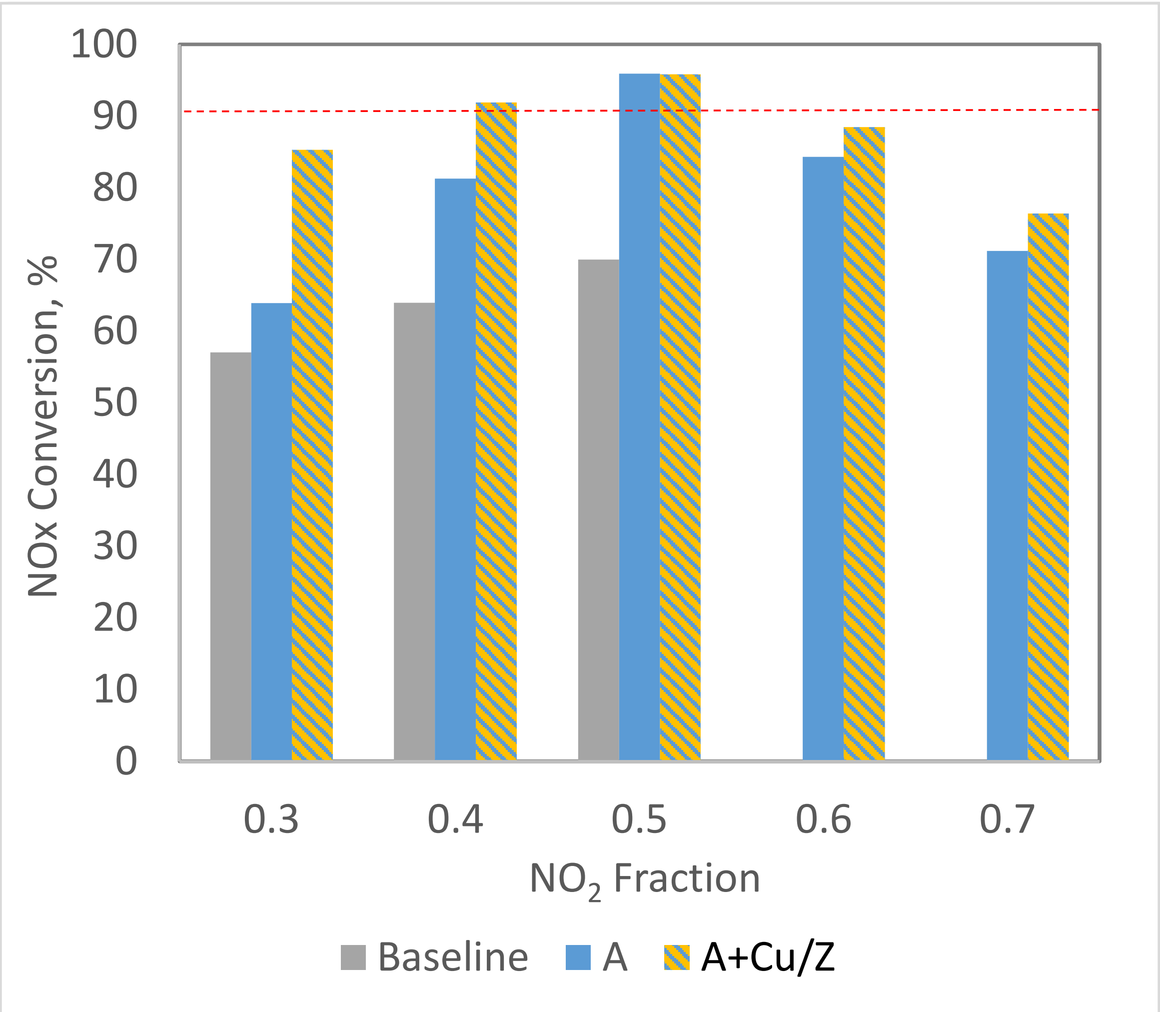
Lab testing with powder at GHSV 100,000h^{-1}, 150^{o}C

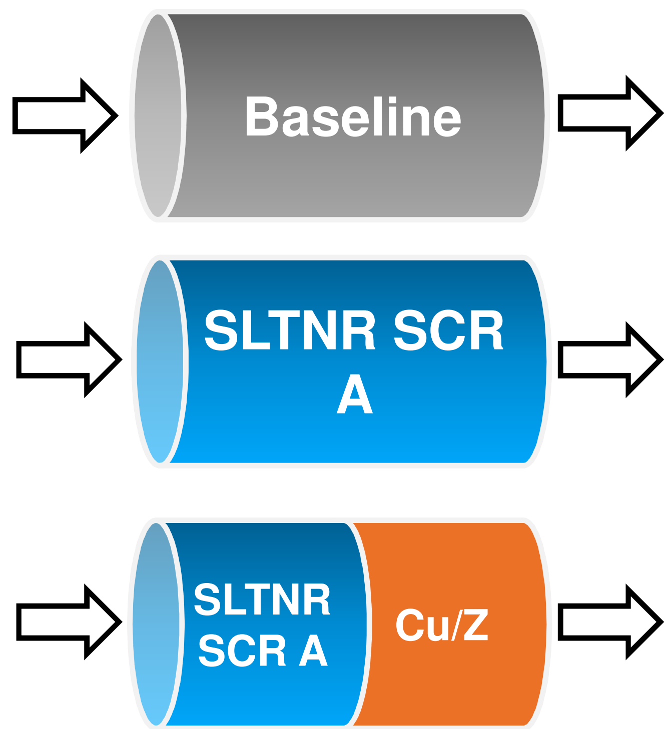




A Low Temperature SCR System Development

Lab testing with powder at GHSV 100,000h^{-1}, 175°C



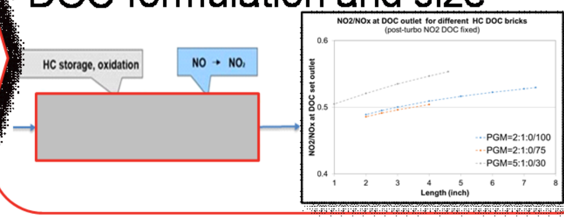


B Integrated High NO2 System Development Path

Attack Approach

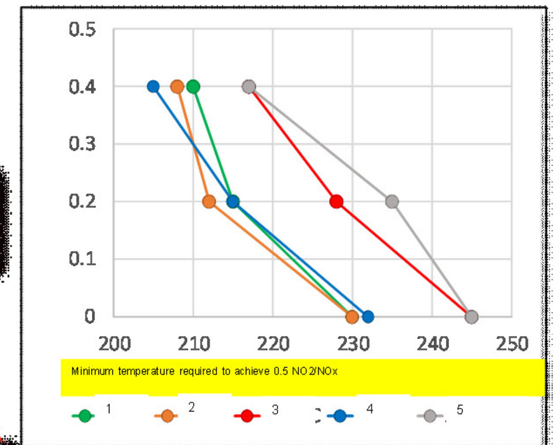
Develop DOC formulation and location together with EGR assistance to optimize NO oxidation performance

Model Based Design of DOC formulation and size



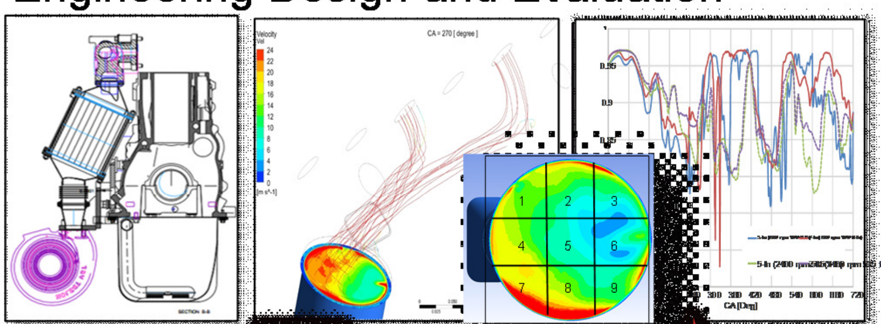
Concept System Mapping

with various PGM, location and volume



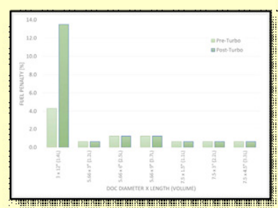
Proof of Concept Pre-turbo DOC

Engineering Design and Evaluation



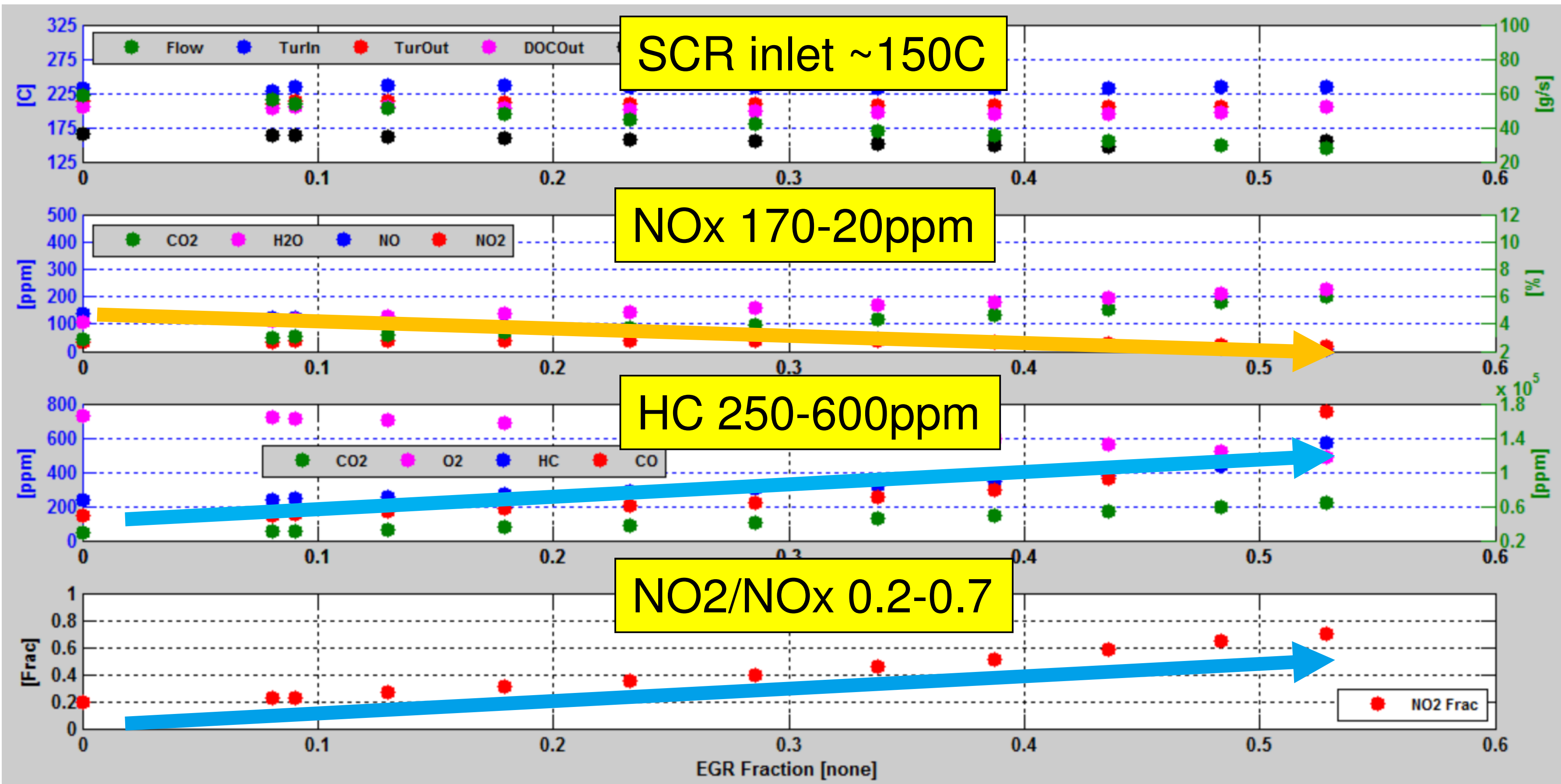
GT Power

to understand impact on engine

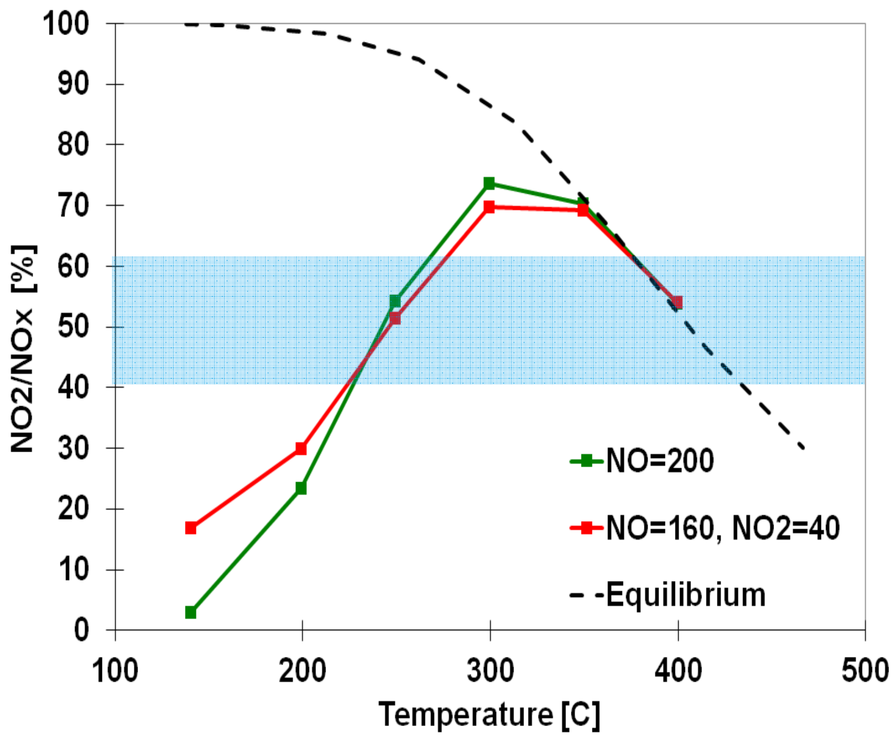


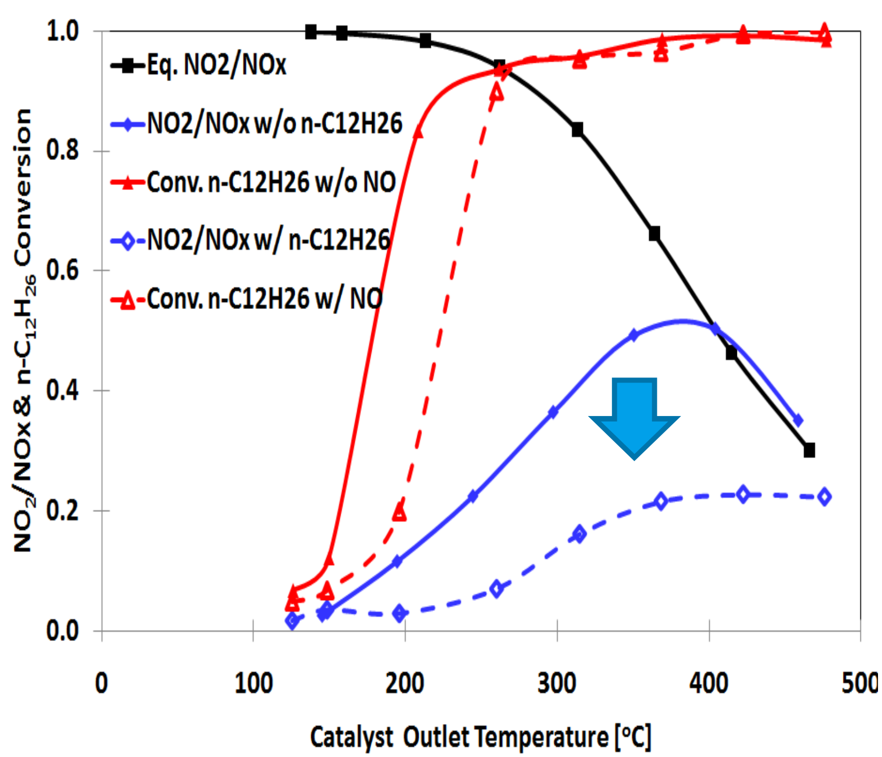
Exhaust manifold re-design → **Engine Demo** → **Commercial Assessment**

B Integrated High NO_2 Strategy
Explore Engine Out NO2 Level

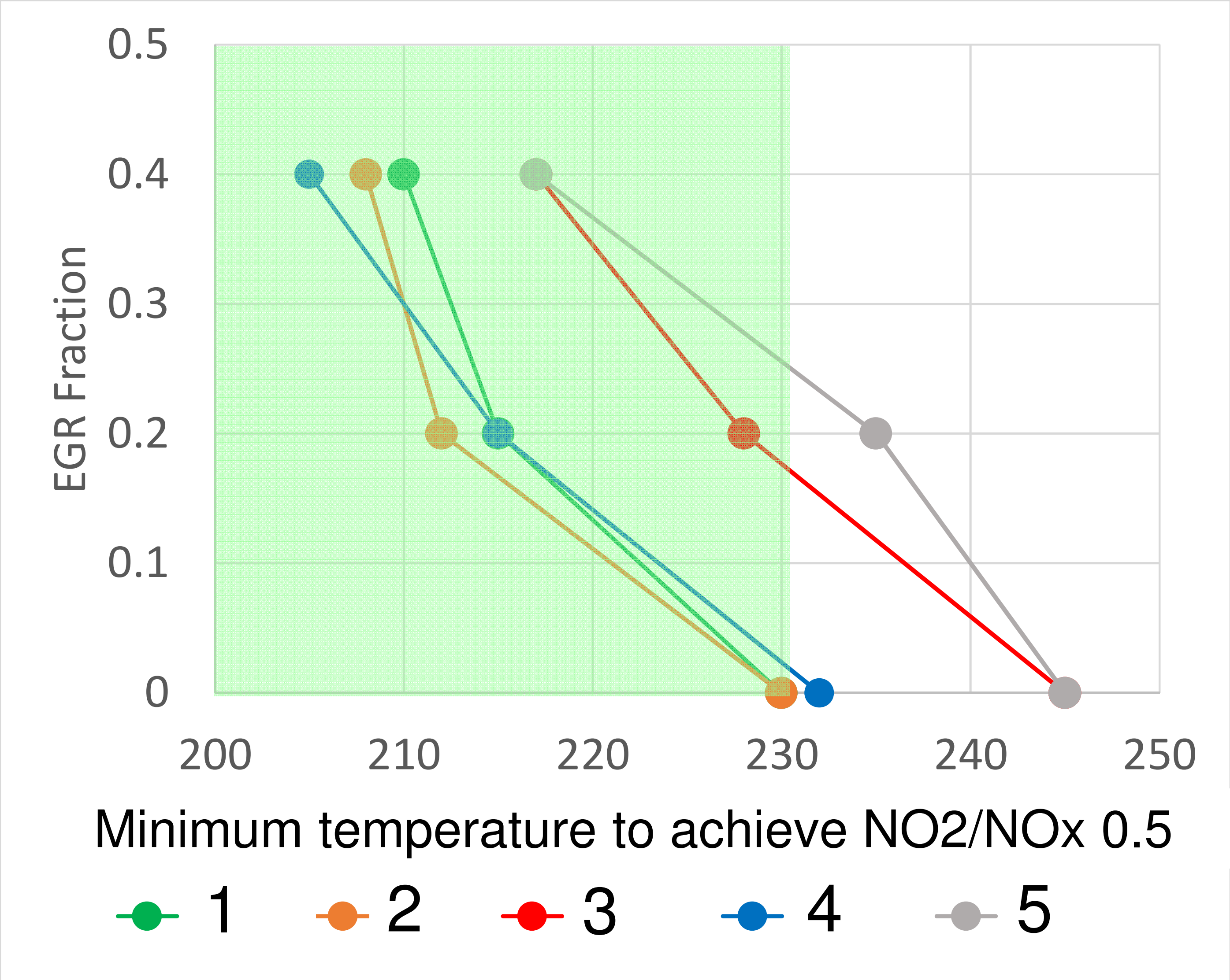


B Integrated High NO2 Strategy Explore DOC Capability and Limitation





B Integrated High NO_2 Strategy
DOC Concept System Performance Mapping

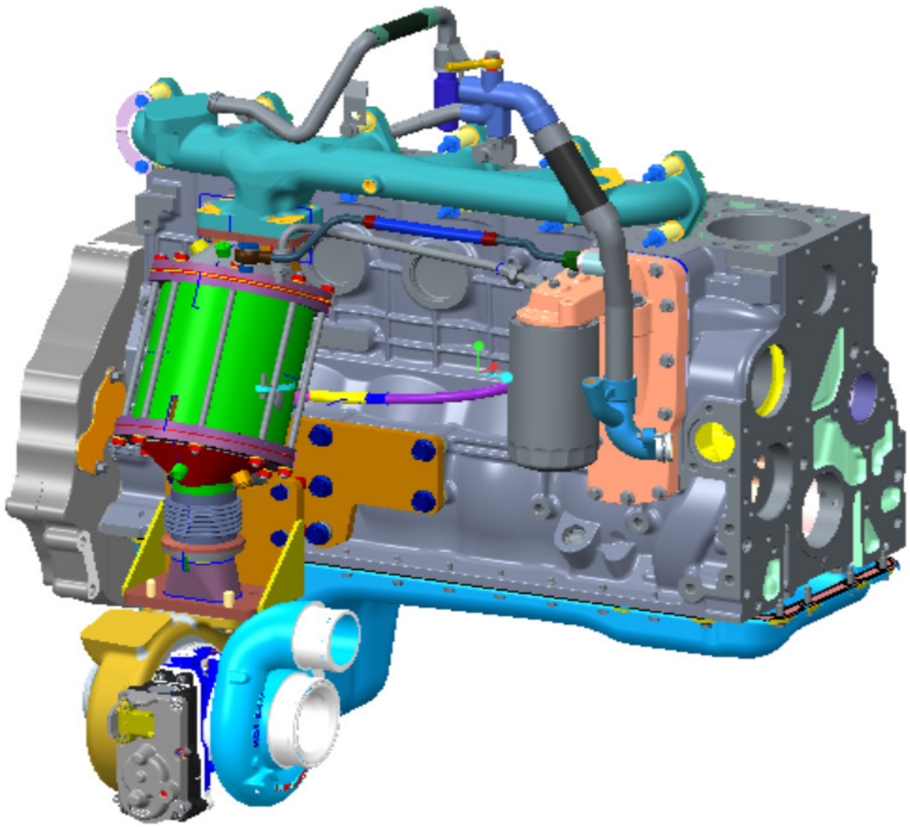


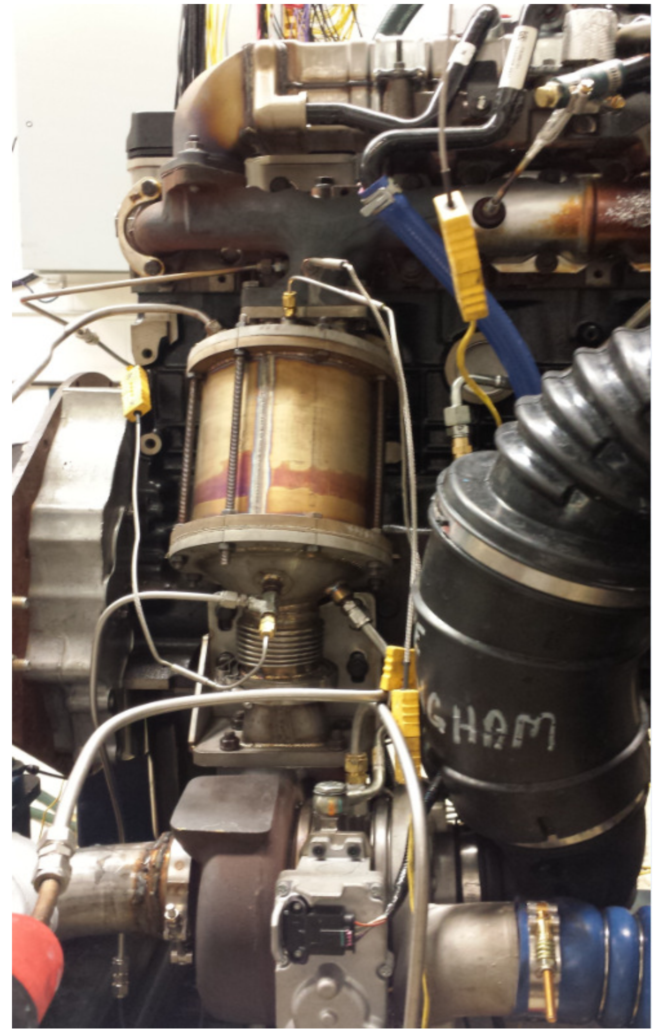
B

Integrated High NO_2 Strategy Proof of Concept Design

On-going: POC Engine test

design optimization to improve transient re

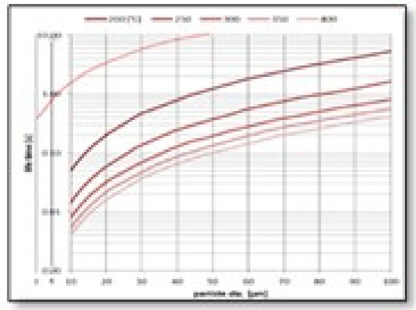




C Reductant Deliver System Development Path

Technology Selection

Droplet size <10micron required at 150°C to minimize deposit, which is not possible with best-in-class mechanical injectors but might be achievable with well designed vaporizer

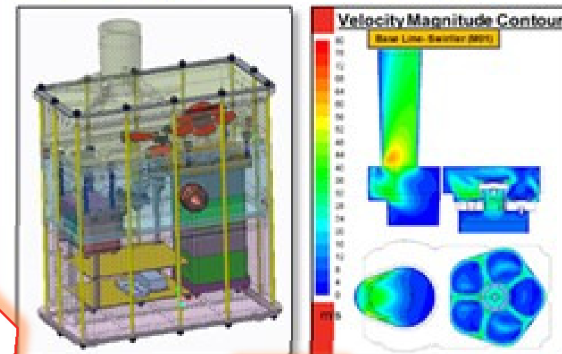


Proof of Concept (I) Preliminary Testing

Droplet Size Distribution Comparison

Averaged Derived Parameter	State of Art Mechanical Injectors	PZT
SMD (micron)	33-55	5~7
Dv90 (micron)	93-150	27

Proof of Concept (II) Component Design



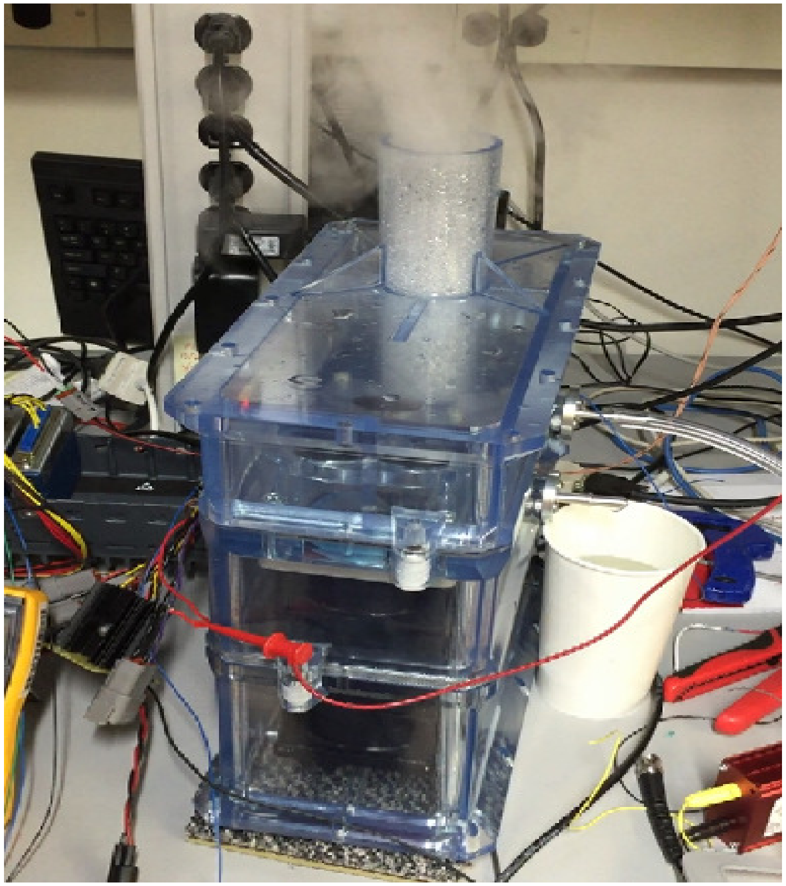
Proof of Concept (III) System Design

Key challenges: metering control, integration, and robustness

Engine Demo to quantify application potentials and gaps

Commercial Assessment

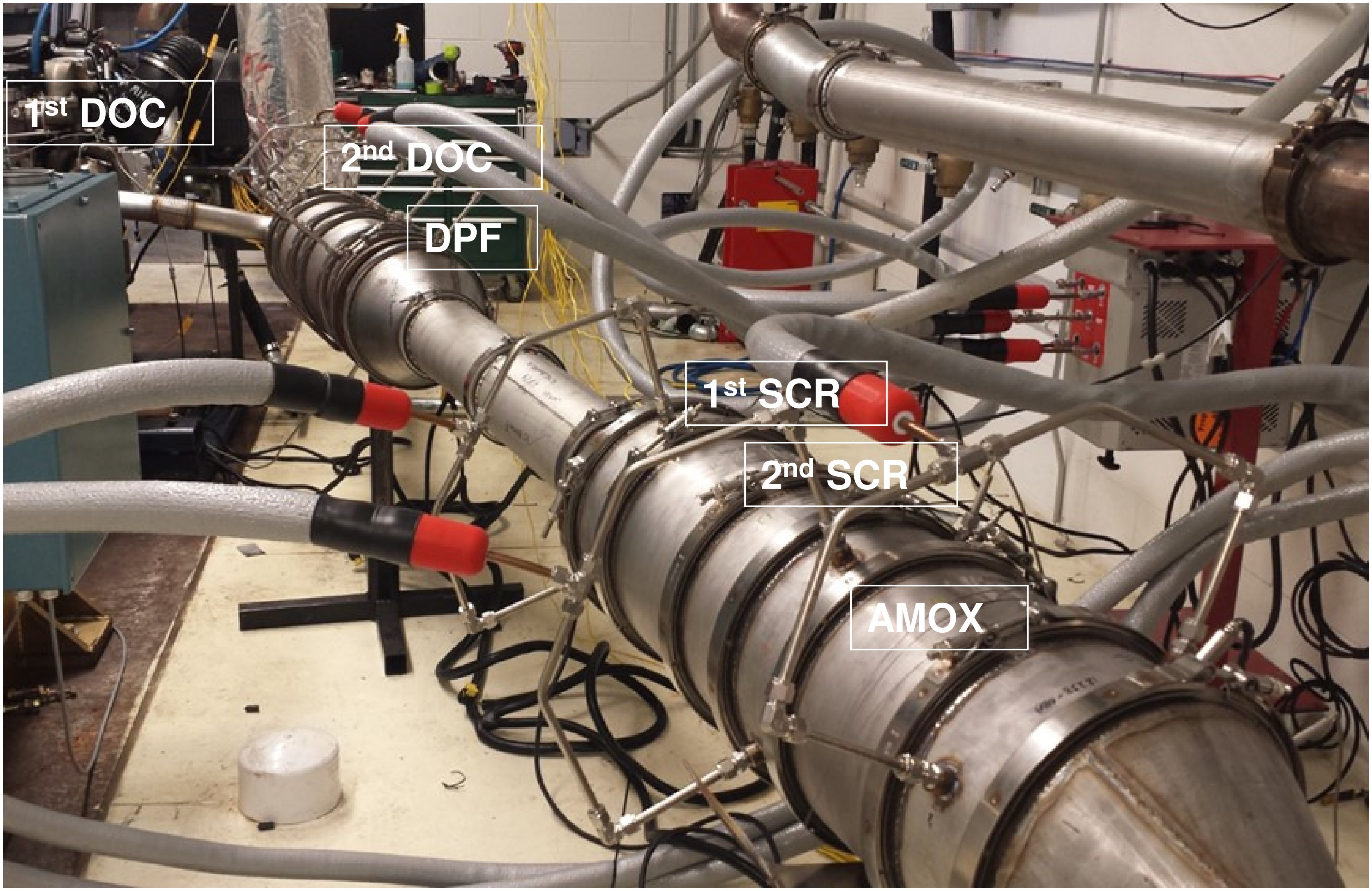
C Vaporizer Design Proof of Concept



Critical Functions and Entitlements	Current Product	SLTNR vaporizer
Min dosing temp (C)	190	(1)
Droplet size (SMD microns)	33	3
Droplet size (DV90 microns)	93	27
Max DEF flow rate (l/hr)	4(2)	0.7(3)

(1) To be evaluated by engine test
(2) Based on ISB with EGR at rated
(3) 0.7 l/hr might be sufficient for SLTNR condition

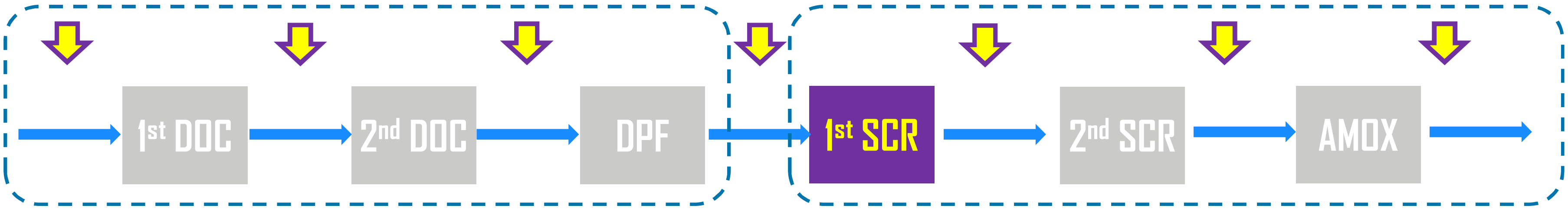
DOC& SCR Prototype System
Engine Test ISB6.7L /360HP

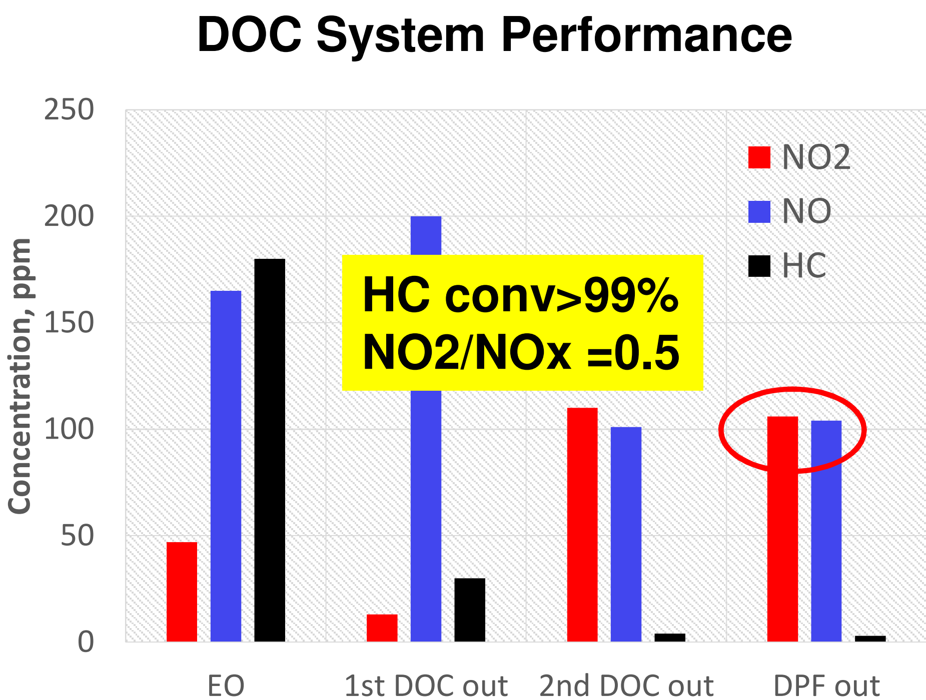


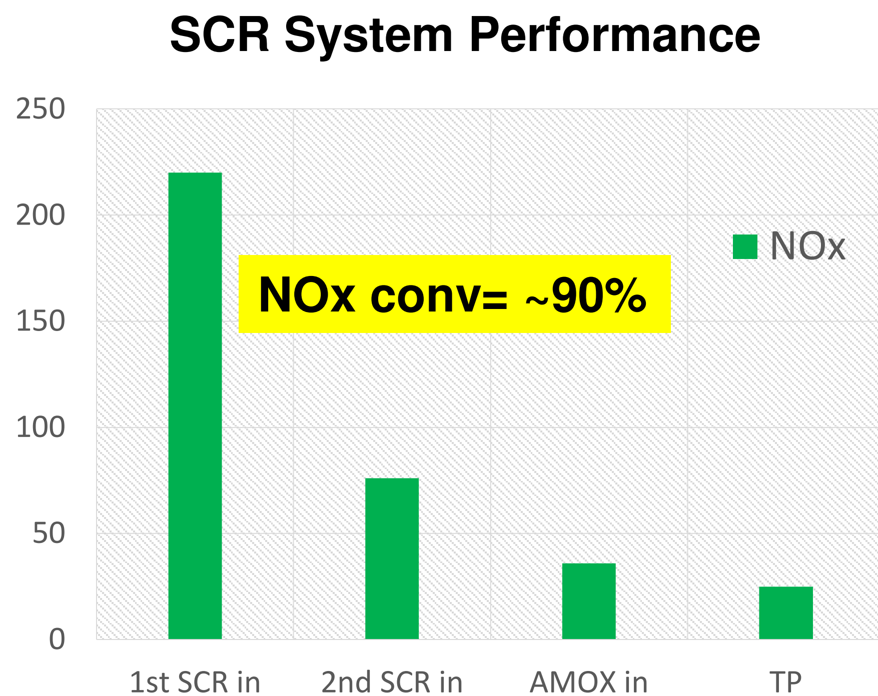
Performance Evaluated for Each Components

Emissions measured at 7+ locations along SLTNR system
SCR instrumented for temperature profile inside brick

❖ Data shown were collected at the end of 16 hours of steady state testing at 1200rpm, ANR ~1.0, EGR ~0.2, SCR 150~160ºC

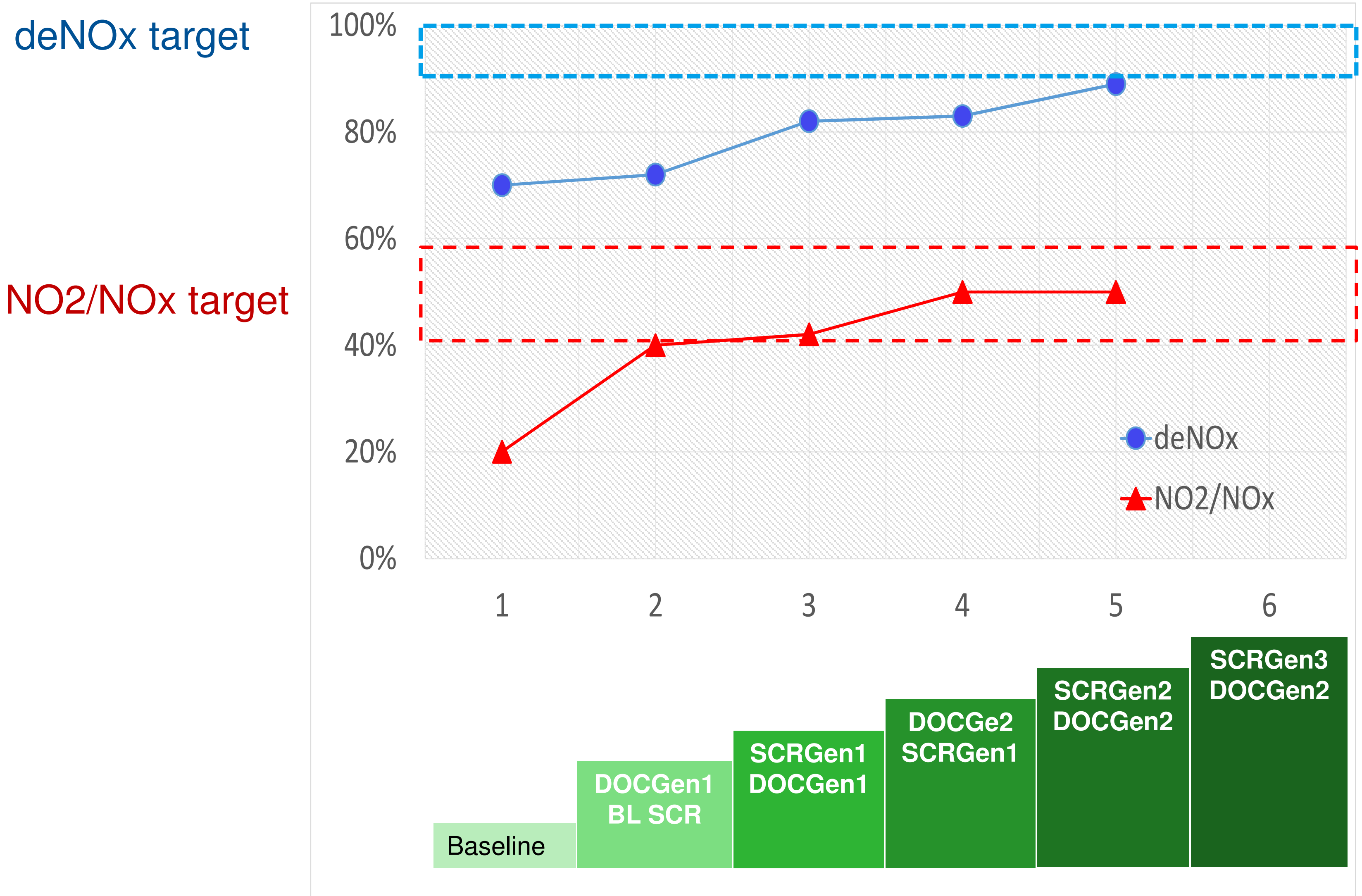






Summary of Incremental Performance Improvements

Conditions：800-1200rpm; EGR 0.2~0.4; SCR 150~160C; 16 hour steady state



Summary

- Achieved ~90% NOx reduction target at SCR ~150°C on engine with gaseous NH_3 dosing and SLTNR SCR and DOC system; further improvements expected by optimizing SCR system;
- Developed ultra sonic reductant delivery technology using DEF to reduce droplet size and therefore minimize requirements of temperature and residence time; this will be tested on engine for demonstration
- Commercial viability will be assessed against identified technology risk factors with percentage of feasibility and confidence, to provide indication of potential for final system

Thank You!

Questions or Comments?