

Cummins/ORNL-FEERC CRADA: NO_x Control & Measurement Technology for Heavy-Duty Diesel Engines

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Project ID:
ACE032

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Overview

Timeline

- Start: FY1998
- Major Revisions: 2001, 03, 06, 10
- Current is 2010-'12 revision
- Finish: September 2012
- % Complete: ~17%

Budget

- Total project budget since 1998
 - DOE share: \$4,950k
 - Contractor share: \$4,950k
- Funding received in FY09
 - \$400k
- Funding for FY10
 - \$400k

Barriers

- *Engine combustion*
 - Combustion uniformity
- *Emissions controls*
 - Catalyst fundamentals, design & control, (& *efficiency*)
- *Engine controls*
 - Variability & diagnostics
 - Fast PM & species diagnostics
- *Durability*
 - Fuel dilution of oil, (& *efficiency*)

Partners

- **ORNL & Cummins Inc.**
- Informal coordination with CLEERS, U.Houston & MI Tech. ACEC (Adv. Comb. & Emiss. Control)

Objectives

Combustion Uniformity:

- Measure cylinder H_2O & PM variations on engine at Cummins
 - Enable improved **efficiency, control and emissions**
- Develop methods to quantify cylinder and cycle uniformity
 - Enable improved **efficiency, control and emissions**
- Improve oil-dilution diagnostic: Fuel-in-Oil (*licensed to Da Vinci Emissions Services*)
 - Enable improved **durability, efficiency and emissions**
 - Lower development **cost** & shorten development **time**

Self-Diagnosing SmartCatalyst:

- Measure intra-SCR catalyst performance distributions
 - Distributed NH_3 storage distribution & SCR reactions
 - Improve catalyst design & control for enhanced **efficiency & emissions control**
- Characterize LNT catalyst reactions and performance distributions
 - Intermediate NH_3 formation and utilization, sulfation & oxygen-storage impacts, water-gas shift reaction
 - Combine models w/ measurements to understand reactions and performance
 - Improved catalyst design & control for enhanced **efficiency & emissions control**

Milestones

2009 Milestone:

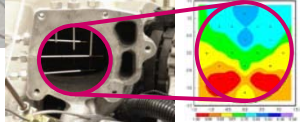
- Demonstrate high-speed exhaust water measurement for assessing combustion uniformity on development engine at Cummins Engine Plant

2010 Milestones (on target for Sept. 2010 completion):

- Characterize variation associated with steady state and transient engine operation.
- Characterize SCR-catalyst performance distribution under select operating conditions.

Approach

ORNL



Develop Diagnostics

Catalyst Applications

Proof-Of-Principle
on Engine

Integrated Partnership
w/ Joint Contributions

Development Needs

Data & Catalyst Understanding

Diagnostics

Iterate on Diagnostics

Other Non-CRADA Programs Benefit Too
DOE, Academia, National Labs, Industry

Cummins

Design Specify Down Select Control

Uniformity Systems Models

Catalyst EGR

Catalyst Applications

Engine Applications

Model Development

Efficient & Clean Engines



Technical Progress: Combustion Uniformity

- Fuel-In-Oil Diagnostic
 - More sensitive, real-time, on-engine measurement of fuel dilution
 - Enables improved **engine calibration, durability, efficiency & emission; and lowers development costs**
 - Licensed to Da Vinci Emissions Services & marketed as DAFIO
 - *Responsive to 2009 Merit Review feedback*
- Fast (3kHz) Exhaust Concentration & PM Measurements
 - Resolves cylinder-to-cylinder & cycle-to-cycle variability
 - Map cylinder combustion uniformity & variations
 - Very relevant to high-EGR systems
 - Enables improved **engine design & control, and reduced emissions**

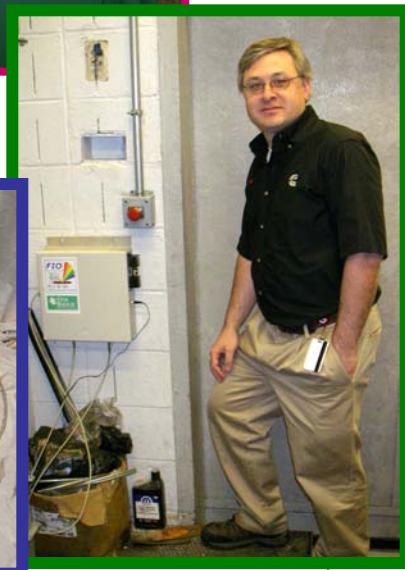
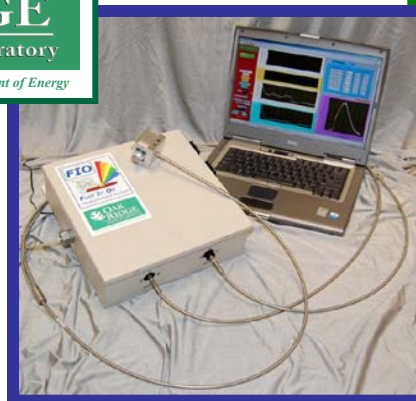
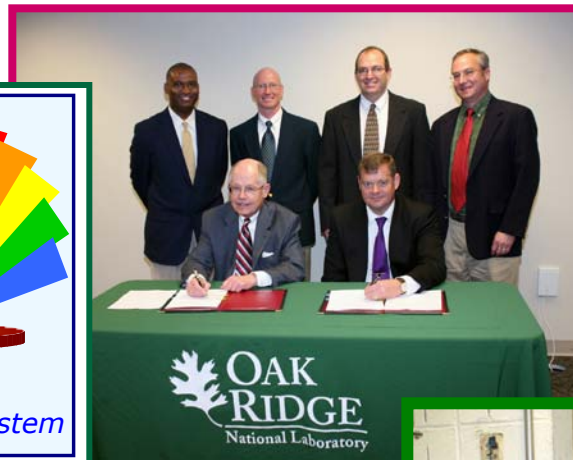
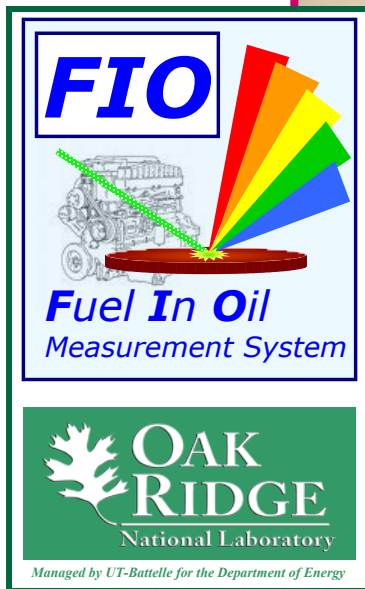
Technical Progress: 1 – Fuel-in-Oil Diagnostic

Fast oil-dilution measurement
for improved calibrations

- FiO provides
 - Fast feedback: ~10min
 - More detailed mapping
 - Local optima revealed
 - Better calibrations!
 - ***Durability, efficiency, emissions***
- Cummins using FiO
- Continued FiO improvement
- ***DAFIO Commercialized!***
- ***2009 SE Region FLC Award
Excellence in Tech Transfer***

Fuel-in-Oil Licensed to Da Vinci Emissions Solutions

(addresses 2009 Reviewer comments)



Tech. Progress: 2a – Fast Exhaust H₂O Measurements

Fast Scan NIR (FSNIR) Laser

Measures engine variations for improved efficiency & emissions

- Objective

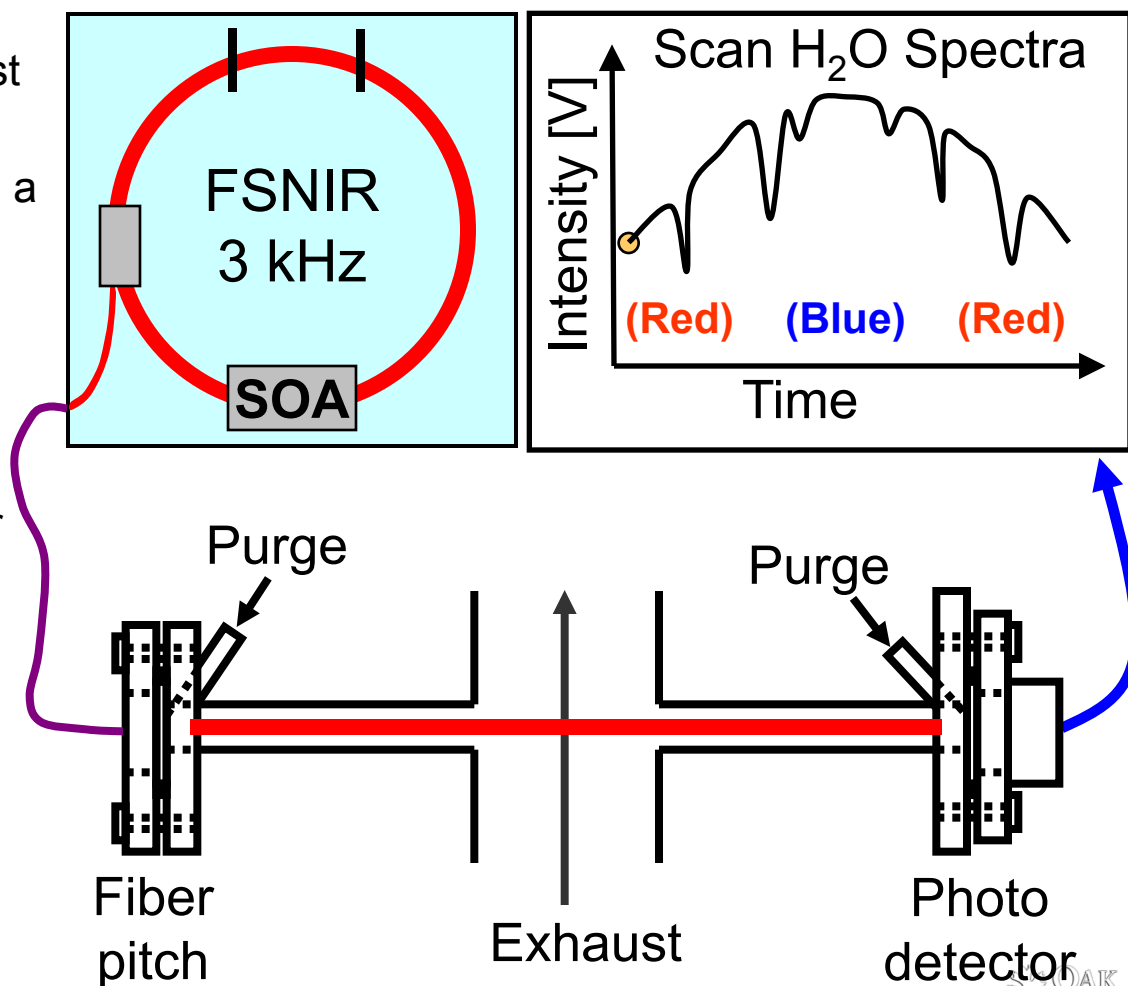
- Resolve cylinder-specific exhaust
- Assess combustion uniformity
- Single-cylinder engine data from a multi-cylinder engine

- Approach

- Fast-Scan NIR measurements
- Fast-Scan NIR laser
 - Version of 45kHz FDMML laser
 - 3kHz scan 1330 to 1380 nm
- [H₂O] via absorbing λ
- PM via non-absorbing λ

- Purpose

- rapid feedback to guide engine development & modeling



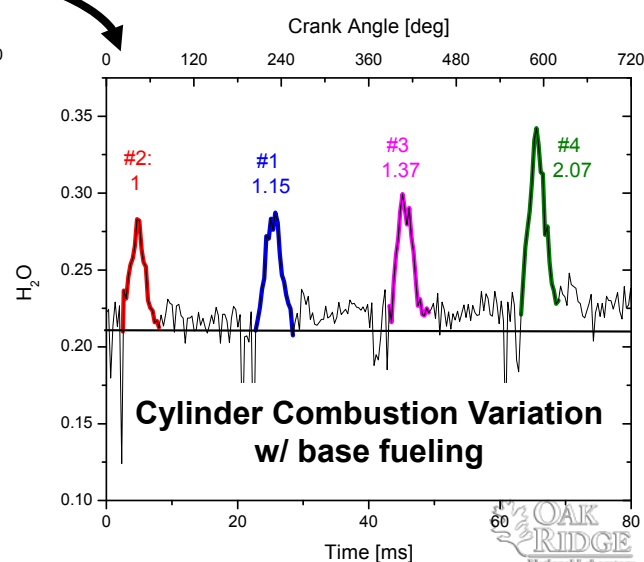
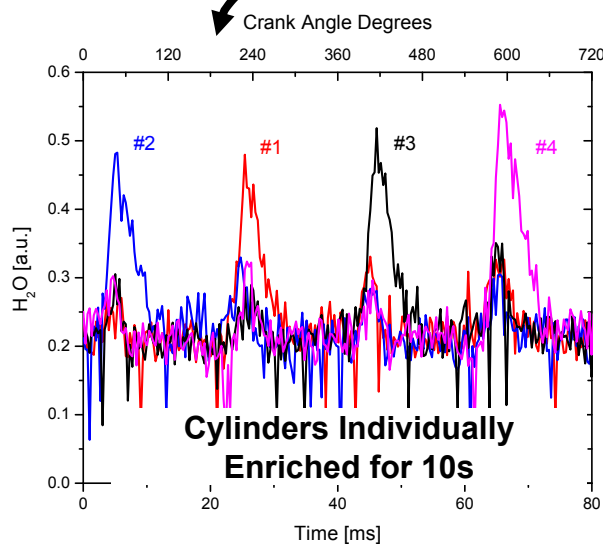
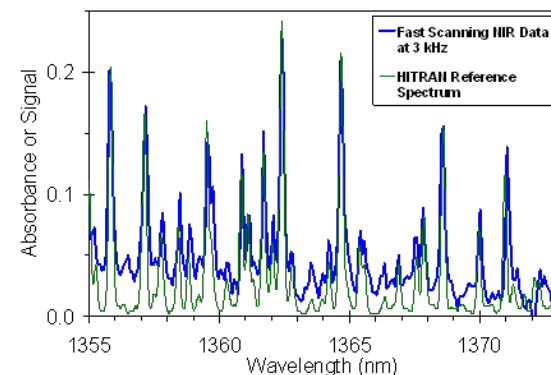
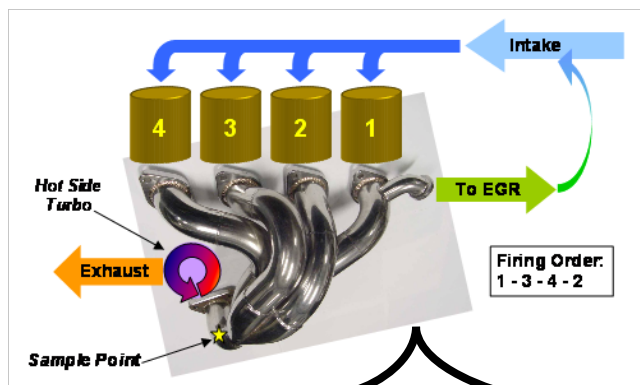
Tech. Progress: 2b – Fast Exhaust H₂O Measurements

- Single cylinder resolution
- Combustion uniformity resolved
- Applications:
 - Map combustion variations
 - Impact of design changes
 - Mitigation strategies
 - Transient EGR feedback
 - Load transients
 - **Improved control and reduced emissions**



Cylinder-Resolved H₂O & PM Measurements Demonstrated

1.7L Mercedes at ORNL

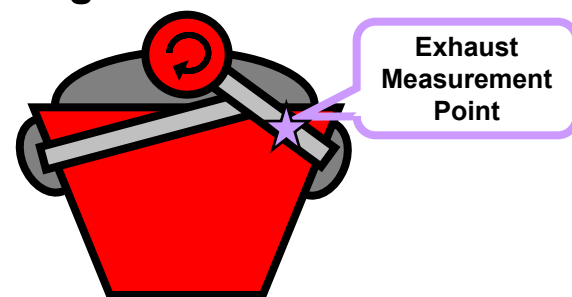
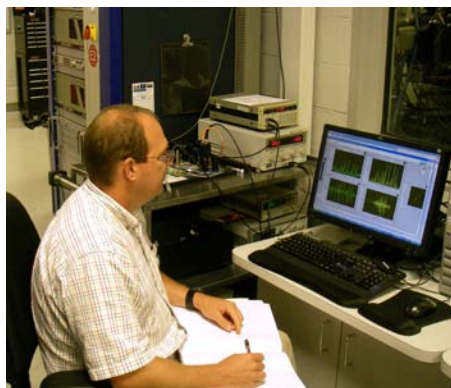


Tech. Progress: 2c – Fast Exhaust H₂O Measurements

- Single-cylinder resolution
- NIR PM tracks Celesco
- More work to do:
 - Alternate optical access design
 - Complex pressure influence
 - Modify for CO₂ measurement
- Shows project approach:
 - Develop instrument in lab
 - Proof on engine at ORNL
 - Apply at Cummins
 - Iterate

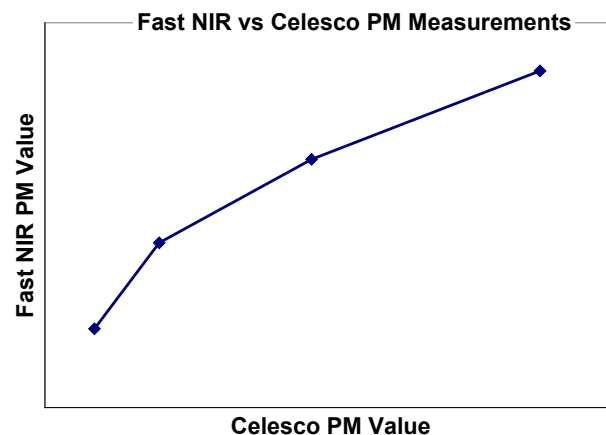
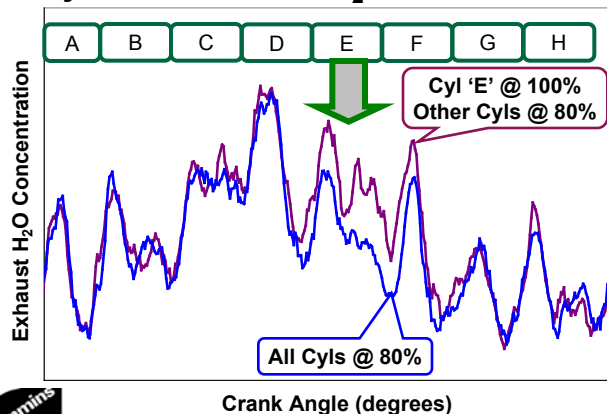
Measurements at Cummins Cylinder-Resolved H₂O & PM Demonstrated

Larger Development Engine at Cummins



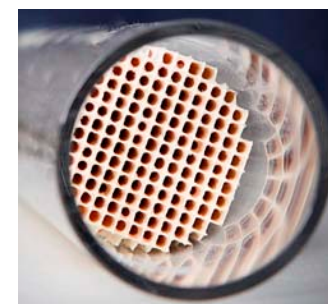
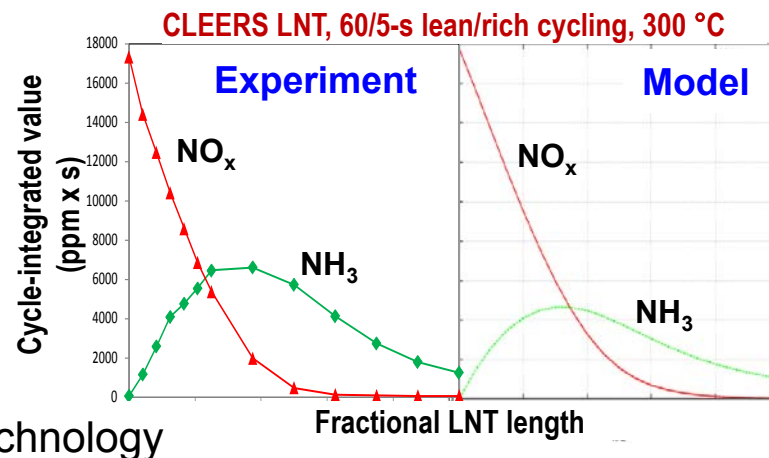
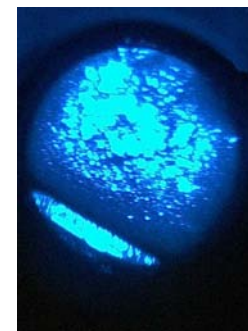
Sample in pipe between
exhaust manifold and turbo

Cylinder-Resolved H₂O Measurements



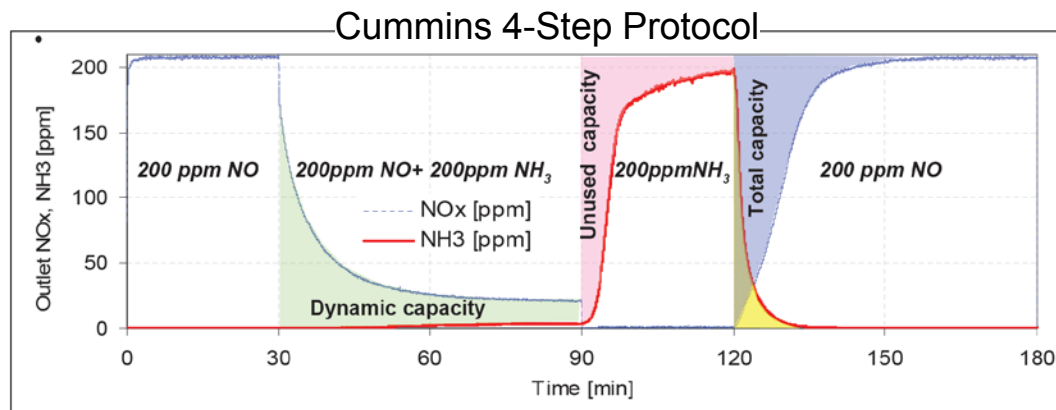
Technical Progress: Self-Diagnosing SmartCatalysts

- Intra-catalyst distributed measurements
 - Provide unique insights & practical solutions
 - SpaciMS received 2009 National FLC Award
 - Optical fiber sensors in development
- Intermediate Ammonia Formation and Utilization
 - Basic understanding of LNT regeneration
 - NH_3 management (lean-gas, light diesel, 2-fuel)
 - Dual LNT-SCR system design
 - Experiments and modeling continuing
 - Joint modeling efforts w/:
 - CLEERS
 - Louise Olsson, Chalmers
 - Petr Koci, Prague Institute of Chemical Technology
- Distributed SCR Reactions & Ammonia Storage
 - Basic understanding of SCR reactions
 - Improve design and performance
 - Identify advanced control strategies for improve performance

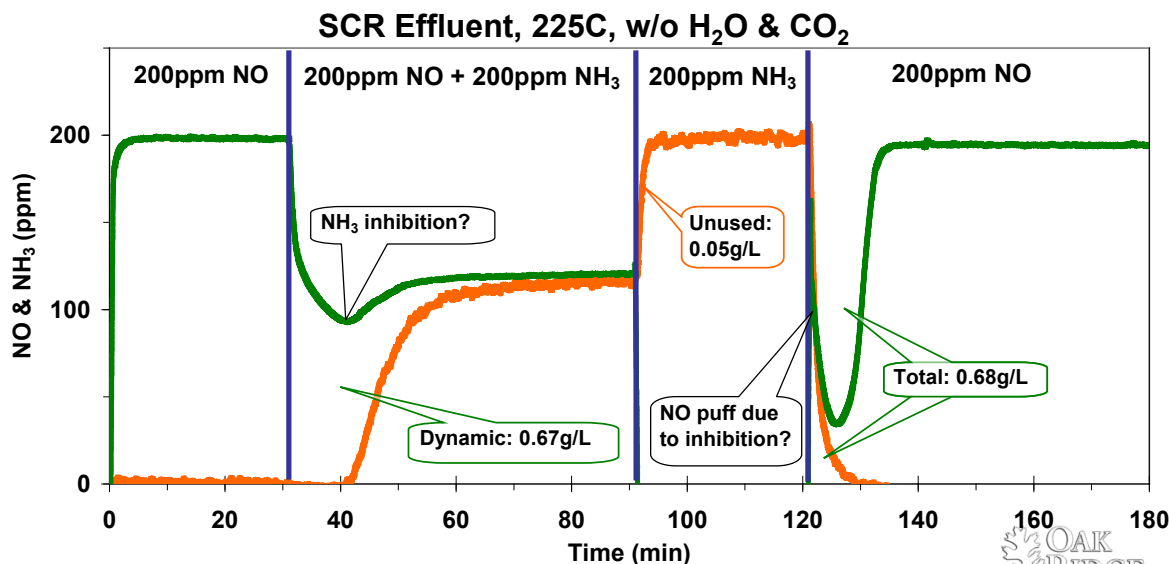


Technical Progress: Intra-SCR Distributed NH₃ Storage

- 4Step Protocol resolves:
 - Dynamic, Unused & Total NH₃ Capacity
- Reactor modified for intra-SCR measurements
 - T > 195°C throughout reactor and up to SpaciMS inlet
- Initial work:
 - CLEERS-Reference Fe SCR
 - 225 & 325°C (225°C shown)
 - SCR effluent
- Qualitative observations:
 - NH₃ inhibition at 225°C vs. 325°C
 - Greater total capacity at 225°C
 - Less unused capacity at 225°C



SCR NH₃ Storage Resolved,
Intra-SCR Storage Distribution Next



Collaborations & Coordination

- Cummins
- CLEERS (*DOE VT funded*)
 - NH_3 measurements & modeling, SCR measurements
- Johnson Matthey - Optical fiber sensor development
- Umicore - CLEERS LNT & SCR catalysts
- U. Houston w/ U. Kentucky, Ford, BASF & ORNL (*DOE VT funded*)
 - Advanced Combustion and Emissions Controls R&D
 - Intra-catalyst reaction distribution measurements
- Michigan Tech. U. (*DOE VT funded*)
 - Similar to U.H. ACEC project above
- LECA (*DOE VT funded*)
 - Exhaust H_2 & O_2 and catalyst measurements
- Prof. Louise Olsson, Chalmers
 - Modeling NH_3 formation and utilization (MS student)
 - SCR measurements (PhD student, @ ORNL June-October)
- Dr. Petr Koci, Prague Institute of Chemical Technology
 - Modeling NH_3 formation and utilization (@ ORNL in June)
- Dr. Alex Goguet, Queen's University Belfast
 - Development of Time-of-Flight SpaciMS
- Dr. Kent Froelund, Da Vinci Emissions Services
 - DAFIO licensed for commercial sales



Future Work

2010 Work:

- Map NH_3 storage distribution throughout SCR catalyst
 - Temperature & NO_2/NO_x sweeps
- Eliminating purge tubes in FSNIR measurement
- Fiber-based O_2 /reductant diagnostic for engine uniformity measurements
- Modeling intermediate NH_3 (joint w/ CLEERS, Chalmers & ICT Prague)
 - Parallel vs. sequential regeneration pathways

2011 Work:

- Assess O_2 /reductant diagnostic on engine
- Measure engine intake uniformity and variations
- Correlate NH_3 storage distributions w/ performance parameters
 - Identify strategies for SCR-catalyst control
- Modeling SCR reactions & NH_3 storage w/ Chalmers
- Fiber-based and other simple NH_3 diagnostics
- Inhibitor impact on SCR catalyst reaction and storage distributions

Summary

- Fuel-In-Oil Diagnostic licensed to Da Vinci Emissions Services
 - Being applied at Cummins for **improved durability, efficiency and emissions**
 - Commercially available for all (*cf. 2009 Review feedback*)
- Cylinder-resolved H₂O & PM measurements demonstrated (*2009 milestone*)
 - Evaluates engine variations and mitigation strategies for **improved efficiency, control and emissions**
 - Applicable to Cummins SuperTruck program
 - Expanding to CO₂ & intake measurements
- Distributed intra-catalyst measurements drive practical advances
 - SpaciMS measurements of SCR NH₃ storage demonstrated
 - Next step is to measure intra-SCR distributed storage & variations w/ conditions
 - Continuing work on LNT NH₃ pathways, and sulfation of LNT WGSR & NO_x storage functions
 - Drives design, modeling, specification and control (OBD) for **improved emissions & efficiency**
- CRADA approach consistently yields practical techniques and solutions
 - E.g., EGR mixing, Fuel dilution, Catalyst & Engine control, Models, SpaciMS, OBD
- Future work focuses on:
 - Studying engine variations and mitigation strategies (*2010 milestone*)
 - Advanced variation diagnostics
 - Distributed intra-SCR chemistry and performance (*2010 milestone*)

