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

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Project ID: ace_32_partridge

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U.S. DOE Program Management Team:
Ken Howden, Gurpreet Singh, Steve Goguen

Overview

Timeline

- Start: FY1998
- Major Revisions: 2001, 03, 06
- Finish: September 2009
- % Complete: 90%
- Extension Planned

Budget

- Total project budget since 1998
  - DOE share: $4,550k
  - Contractor share: $4,550k
- Funding range: $250-450k/year
- Funding received in FY08
  - $450k
- Funding for FY09
  - $400k

Barriers

- *Emissions controls*
  - Catalyst fundamentals, design & control, (& *efficiency*)
- *Engine controls*
  - Variability & diagnostics
  - Fast PM & O_2 diagnostics
- *Durability*
  - Fuel dilution of oil , (& *efficiency*)

Partners

- ORNL
- Cummins Inc.
- Informal coordination with CLEERS

Objectives

Engine-Systems:

- Apply oil-dilution diagnostic on development engine at Cummins
  - Enable improved ***durability, efficiency and emissions***
  - Lower development ***cost*** & shorten development ***time***
- Develop and apply methods to quantify cylinder and cycle variations
  - Enable improved ***efficiency, control and emissions***

Instrumentation & Bench:

- Characterize sulfation impact on LNT catalyst reactions
  - Intermediate NH_3 formation and utilization & water-gas-shift reaction (WGSR)
  - Improved catalyst design & control
  - Enhanced ***efficiency & emissions control***
- Characterize NH_3 chemistry in LNT with oxygen-storage component
  - Umicore, CLEERS-reference catalyst
- Measure intra-SCR catalyst performance distributions

Milestones

2008 Milestone:

✓

- Characterize sulfation effects on LNT reductant reactions
  - E.g., intermediate NH_3 formation & utilization, WGSR

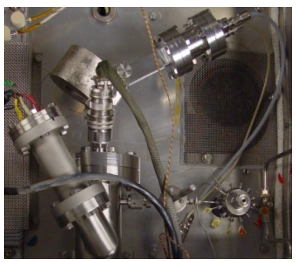
2009 Milestone:

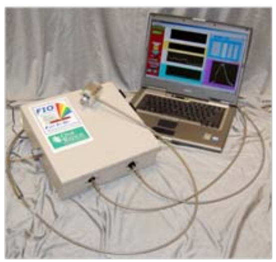
- Demonstrate measurement capability for characterizing axial performance of SCR catalyst

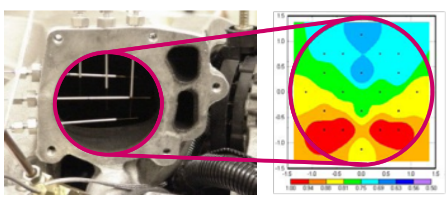
Approach

ORNL

Develop Diagnostics, & Apply for System & Device Insights



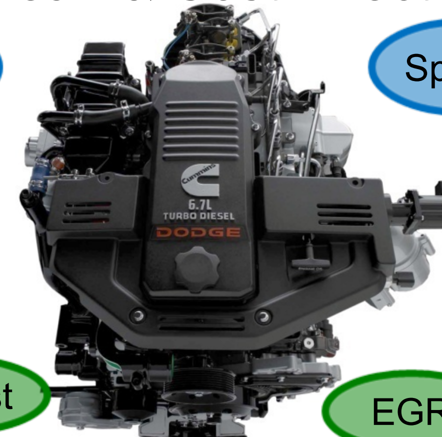




Cummins

Apply Diagnostics & Insights to Develop Efficient, Clean & Cost Effective Diesels

Design
Specify
Down Select
Control
Models
Uniformity
Systems
Catalyst
EGR



Non-CRADA Benefactors

DOE
CLEERS
National Labs
Work For Others
Industry
Universities
Fuel Cells
Fuel Reformers

Picture of engine courtesy of Cummins Inc., and used with permission

Technical Accomplishments: *Engine-Systems*

- Fuel-In-Oil Diagnostic
  - Enables improved engine calibration, durability, efficiency & emission

- Optical Backscatter Probe
  - Resolves cylinder-to-cylinder & cycle-to-cycle variability
  - Very relevant to high-EGR systems
  - Enables improved engine control & reduced emissions

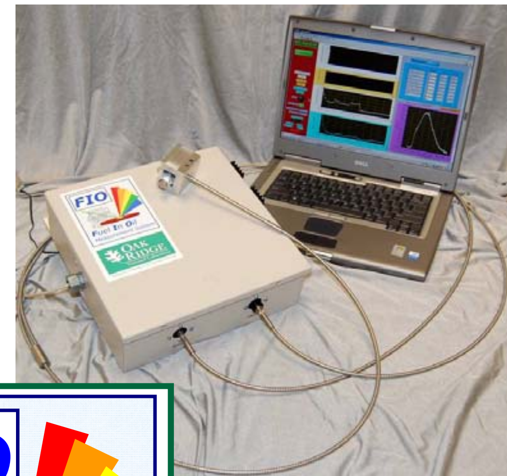
Technical Accomplishments: 1 – Fuel-in-Oil Diagnostic

Fast oil-dilution measurement for improved calibrations

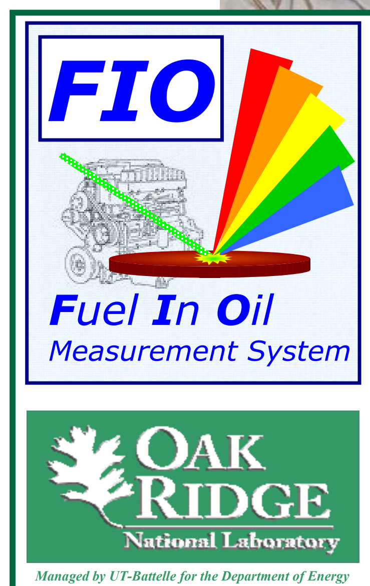
Fuel-in-Oil Transferred to Cummins

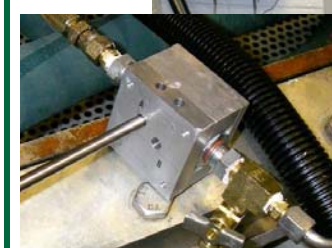
- Conventional ASTM
  - Extractive
  - Off-site (slow: days)
- FiO provides
  - Fast feedback: ~10min
  - More detailed mapping
  - Local optima revealed
  - Better calibrations!
    - ***Durability, efficiency, emissions***
- CRADA work in FY07-08
- Cummins funded technology transfer

FIO instrument shown with control software (right)



Cummins partner Mike Cunningham with installed FIO instrument at Cummins (below)





Fiber optic probe installed in engine oil line (above)

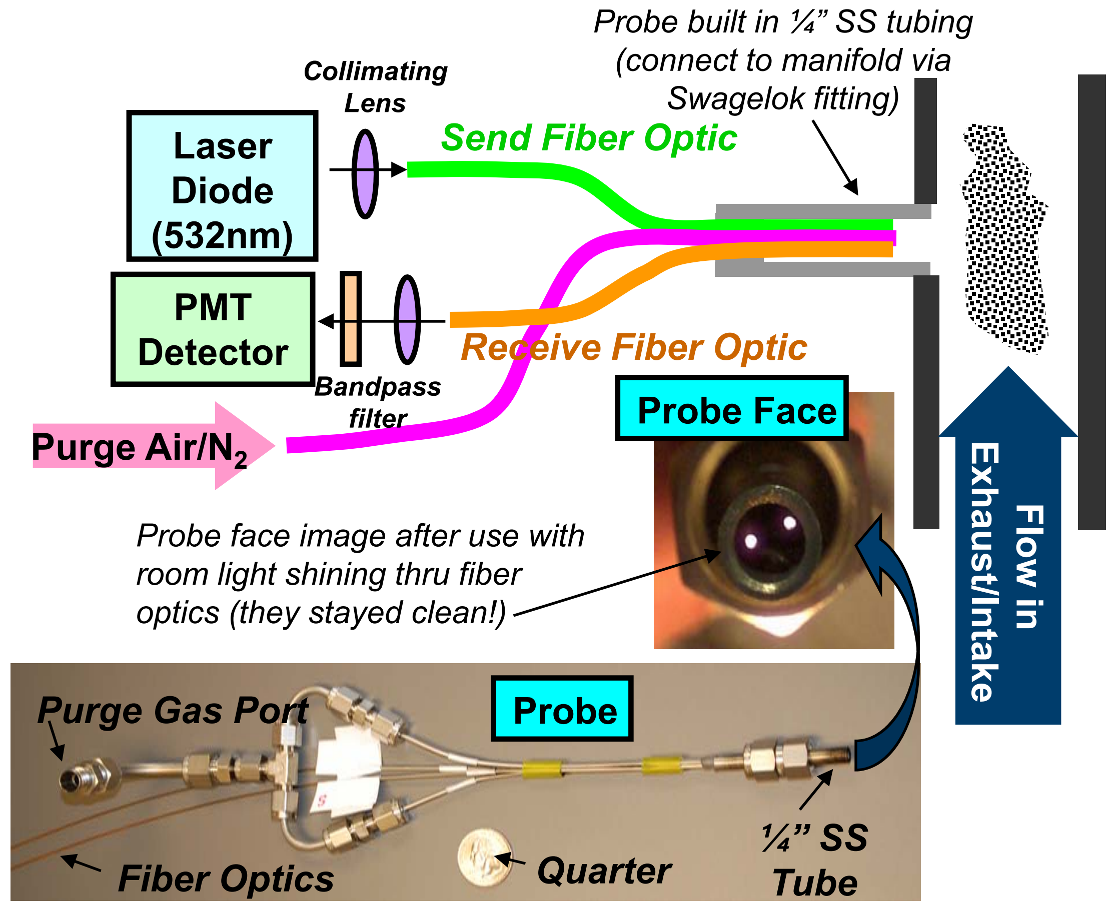
Technical Accomplishments: 2a – Fast PM Diagnostic

Optical Backscatter Probe

Measures engine variations for improved emissions & efficiency

- Objective
  - Develop tool for rapid cycle- & cylinder-resolved PM emissions
  - Model after Fuel-in-Oil diagnostic
- Approach
  - Optical-based probe
  - Inexpensive to multiplex for multiple point measurements
  - Simple and easy to implement In comparison to other techniques*
- Purpose
  - rapid feedback to guide development

Optical Backscatter Probe Demonstrated on Diesel Engine

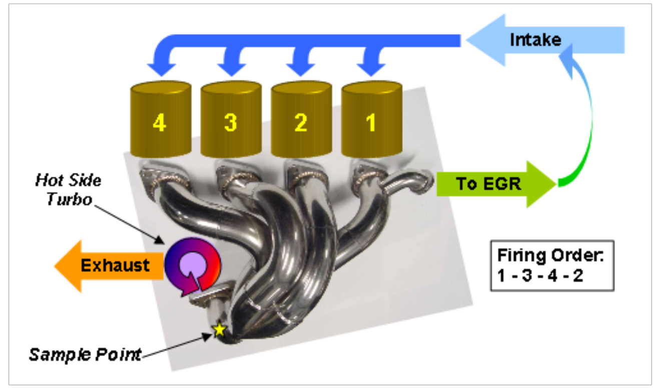


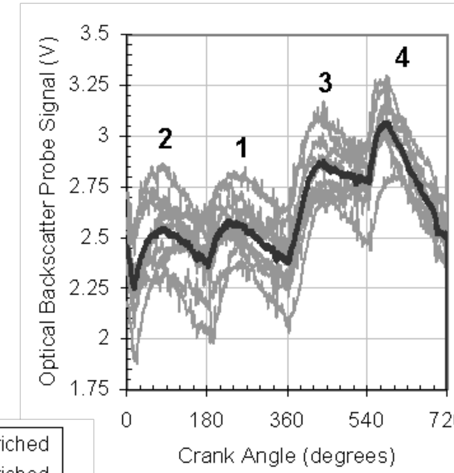
* Scattering: Tree et al., SAE940270. LII: Witze et al., SAE2005-01-0186. Extinction: Scherrer et al., SAE810181. Polarization: Hunt et al. SAE982629,

Technical Accomplishments: 2b – Fast PM Diagnostic

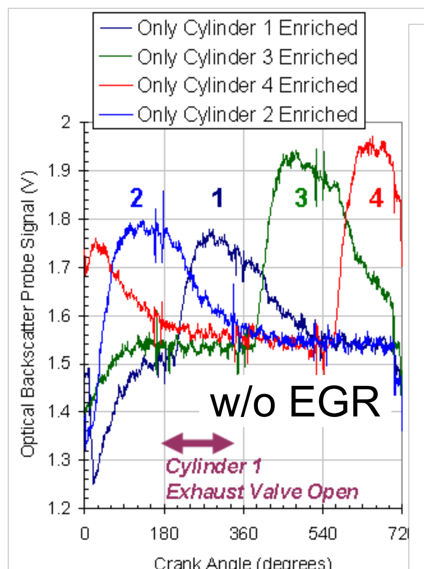
- Baseline cylinder & cycle variations resolved
  - Cylinders 3 & 4 PM higher
  - ~ 20% cyc-to-cyc variations
- Fueling variations resolved
- EGR is from cyl.s 1 & 2
- OBP applications:
  - Dispersion mapping
  - Transient EGR feedback
  - Load transients
  - Impact of design changes
  - Mitigation strategies
  - ***Improved control and reduced emissions***
- More work to do:
  - Improved sensitivity

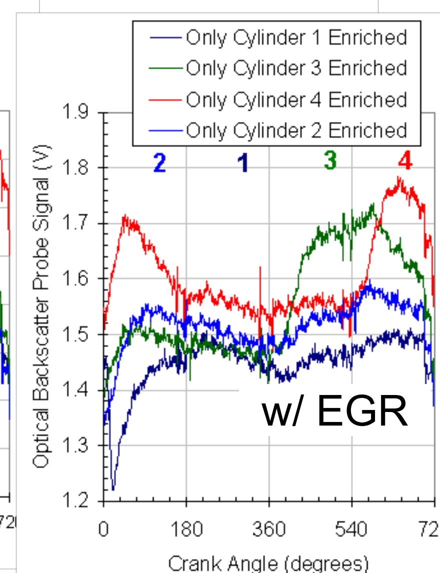
Cylinder- & Cycle-Resolved PM Measurements Demonstrated





Base cyc. & cyl. variations

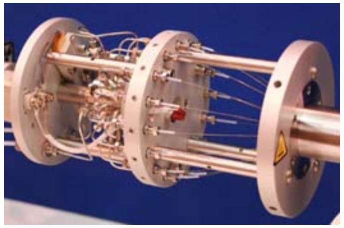




Cylinder-specific fueling variations

Technical Accomplishments: *Instrumentation & Bench*

- Intra-catalyst distributed measurements
  - Provide unique insights & practical solutions
  - SpaciMS received R&D100 and National FLC Awards
  - Further improved SpaciMS & other methodologies

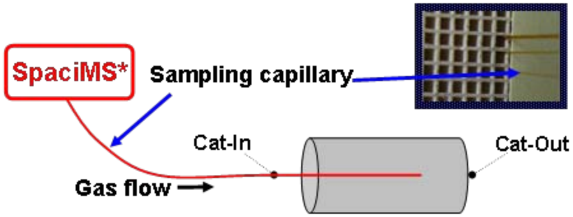


2008 Award

2009 Award

- Sulfation impact on LNT Water Gas Shift Reaction
  - Improved catalyst models & control
  - Elucidates basic catalyst chemistry
  - Reduced regeneration & De-SO_x fuel penalty
- Sulfation impact on Intermediate Ammonia Formation and Utilization
  - Basic understanding of LNT regeneration
  - NH_3 management
  - Hybrid LNT-SCR system design
- Intermediate NH_3 modeling
- DeS Kinetics and Surface Sulfur Types
  - Joint w/ CLEERS

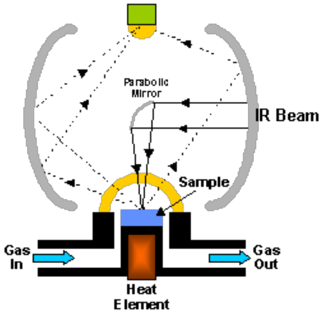
Bench-Scale Core Reactor
In Situ Intra-Channel Speciation



**Spatially Resolved Capillary Inlet Mass Spectrometer*

Micro Reactor

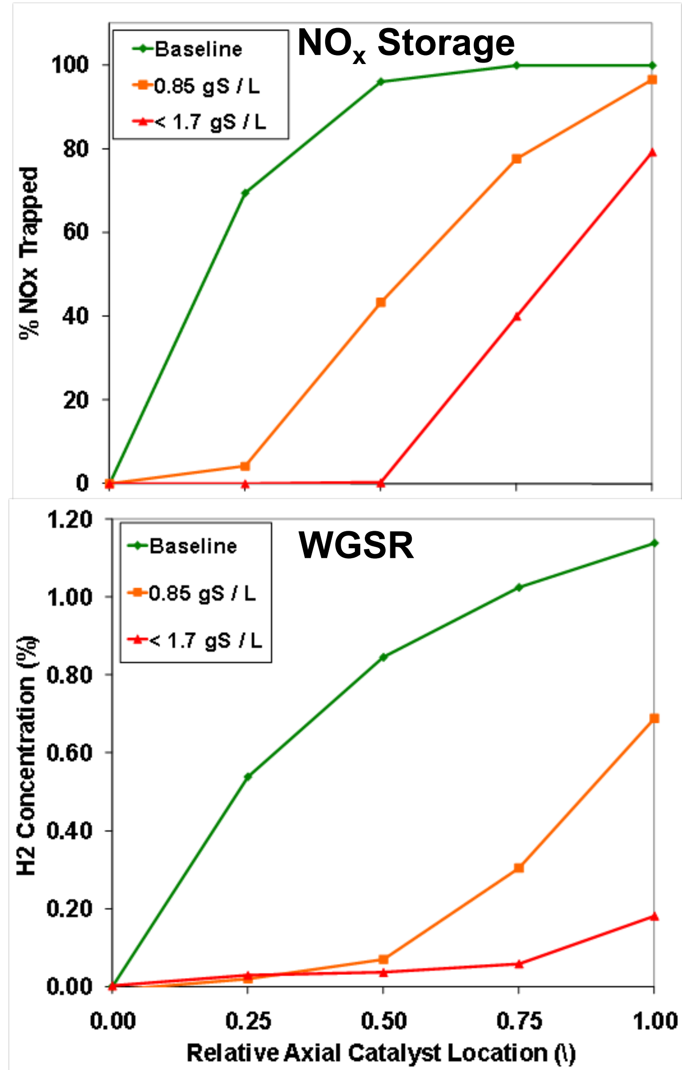
DRIFTS Reactor



Technical Accomplishments: 3a – Catalyst Control

WGSR is a Sensitive Indicator of LNT Catalyst State

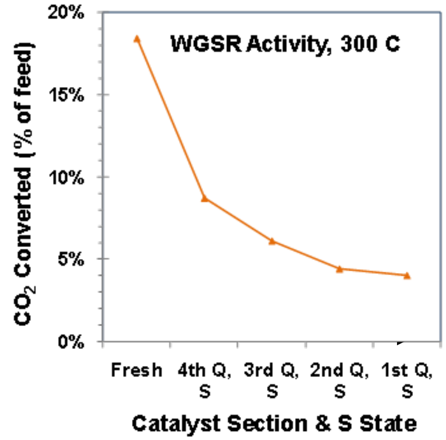
- Water Gas Shift Reaction:
  - $CO + H_2O \rightarrow H_2 + CO_2$
  - Converts CO to H_2
  - Use for $DeNO_x$ & $DeSO_x$
- Investigated 3 Sulfation levels
  - 0, 0.85 & <1.7 gS/L_{cat}
- Progressive NO_x storage loss
  - ~ plug like
  - Broadened storage
- WGSR-S front leads NO_x-S front
  - WGSR more sensitive to S than NO_x storage



Technical Accomplishments: 3b – Catalyst Control

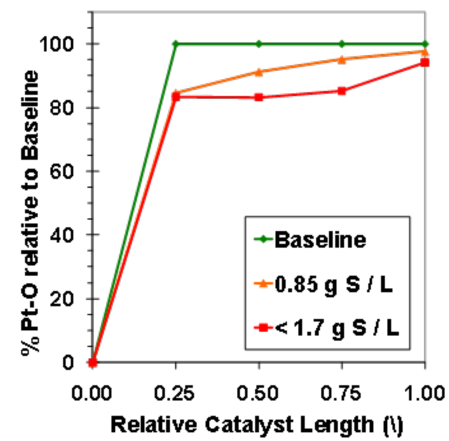
- **S has nonlinear impact on WGSR**
  - Small initial S dose has a major impact on WGSR (Fresh vs. 4th Q)
  - 4th Q has significant NO_x capacity
- **Little S-impact on Pt availability**
  - Minor S-impact on availability of Pt to O
    - 80-95% Pt-availability compared to fresh
  - Availability of Pt to CO unchanged
  - Pt sites are available after sulfation
- **WGSR loss not due to Pt-S blocking**
  - At 300 C
- **S must degrade WGSR via other mechanisms, e.g.:**
  - CO or H_2O activation (Pt e- density change)
  - Inhibition of spillover between Pt and oxides
  - Blocking of Pt-support interfacial sites
  - Other…?

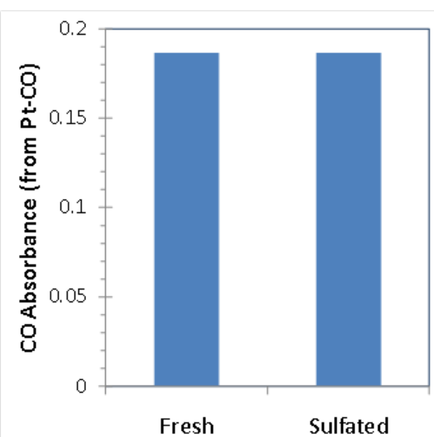
Sulfation Impacts NO_x-Storage & WGSR Chemistry Differently



WGSR Activity via Microreactor at 300C

Pt-O via SpaciMS at 325C



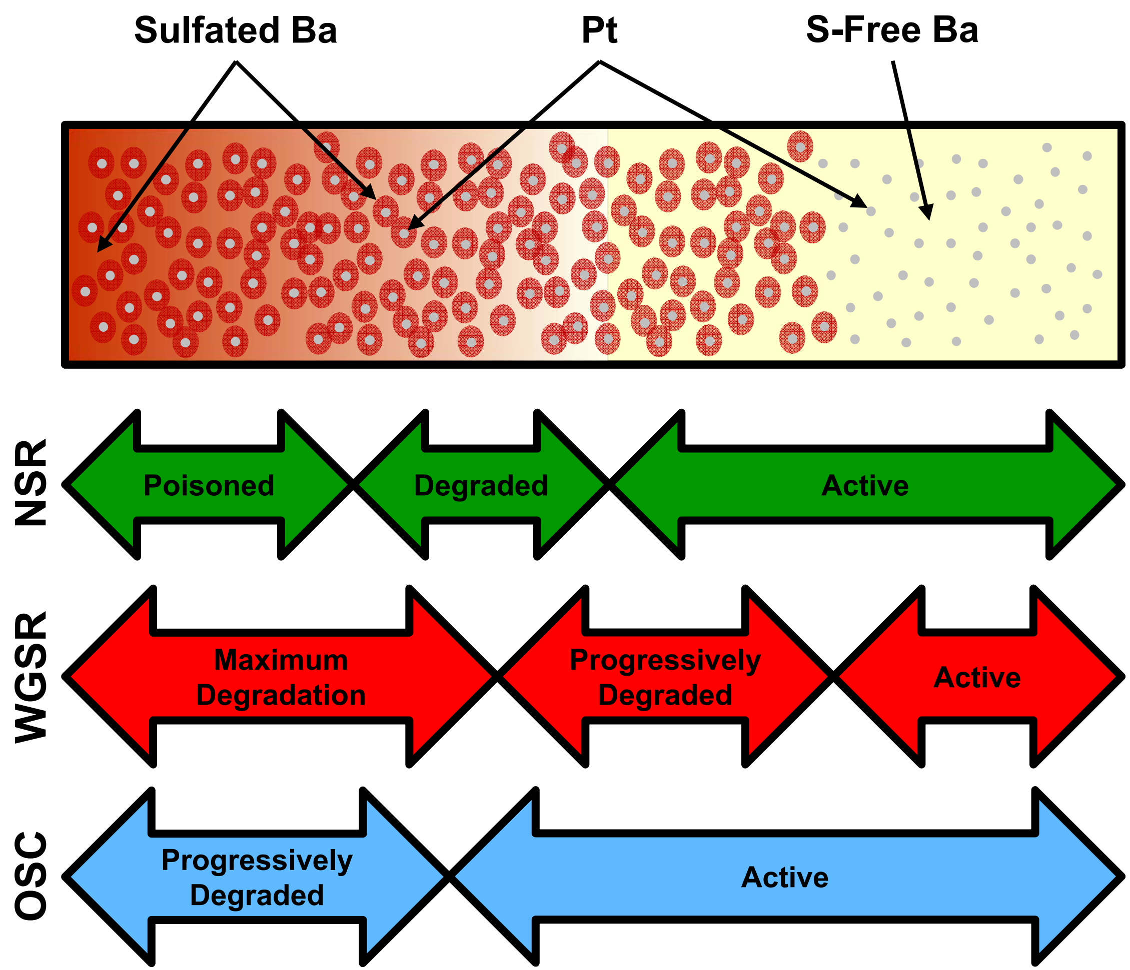


Pt-CO via DRIFTS at 300C

Technical Accomplishments: 3c – Catalyst Control

- Catalyst insights:
  - Sulfation impact on different LNT functions
  - Distribution of S impact
  - Conceptual understanding of LNT chemistry
- Use for catalyst design:
  - Improved model accuracy
  - Device size/capacity
- Use for OBD & control:
  - Cummins Control Patent (US Patent App. 20080168824)
- Better emissions control & efficiency

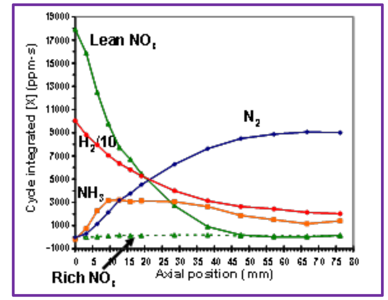
Understanding Catalyst WGSR Enables Better Emissions Control



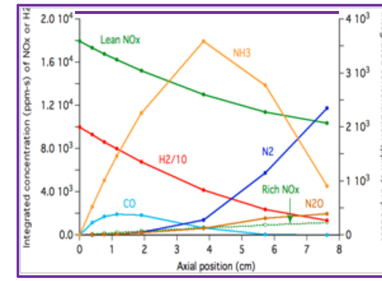
Technical Accomplishments: 4 – NH_3 & DeSulfation

- Sulfation Impact on Intermediate NH_3
  - Experiments complete
  - Used Umicore CLEERS reference LNT catalyst
    - contains Ce oxygen storage component
  - Reducing & analyzing data

Measurements

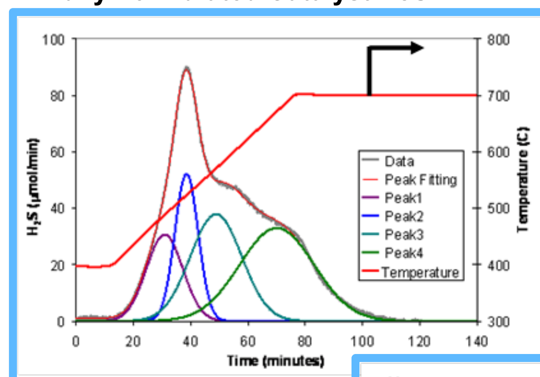


Simulation



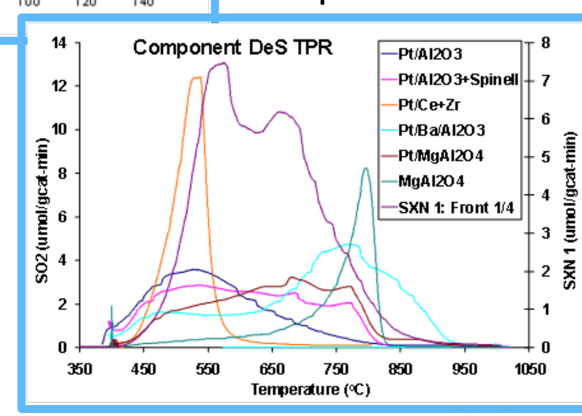
- Intermediate NH_3 Modeling
  - Joint w/ CLEERS
  - Investigate Direct-H_2 vs. Intermediate-NH_3 regeneration pathways
  - Working to build on CLEERS LNT model

Fully Formulated Catalyst DeS TPR



- Surface Sulfur Types & DeS Kinetics
  - Joint w/ CLEERS
  - Using fully formulated Umicore catalyst
  - Studying reference catalyst components
  - Partial desulfation of catalyst sections
  - Correlating partial DeS w/ NO_x performance

Component DeS TPR



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for the Department of Energy

Future Work

2009 Work:

- Investigate Optical Backscatter Probe in off-axis excitation/detection mode
- Fiber based diagnostics for cylinder-resolved variability measurements
- WGSR sulfation impacts work: origins of degradation
- Modeling intermediate NH_3 (joint w/ CLEERS)
  - Parallel vs. sequential regeneration pathways
- De-Sulfation kinetics and surface-S types (joint w/ CLEERS)
- Demonstrate measurement of distributed intra-SCR performance ***(milestone)***
- Pursue CRADA continuation at Cummins' request

2010 Work:

- Apply diagnostics to quantify engine variability and mitigation strategies
- Characterize distributed response of SCR to operation changes

Summary

- Fuel-In-Oil Diagnostic delivered to Cummins
  - Being applied for ***improved durability, efficiency and emissions***
- Cylinder- & cycle-resolved PM measurements demonstrated
  - Applicable to studying engine variations and mitigation strategies for ***improved efficiency, control and emissions***
- Distributed intra-catalyst measurements drive practical advances
  - Intermediate NH_3 regeneration pathway
  - WGSR sulfation front leads that of NO_x storage ***(2008 milestone)***
  - Drives design, modeling, specification and control (OBD) for ***improved emissions & efficiency***
- CRADA approach consistently yields practical techniques and solutions
  - E.g., EGR mixing, Oil dilution, Catalyst & Engine control, Models, SpaciMS (R&D 100 2008 Award FLC 2009 Award), OBD
- Future work focuses on:
  - Studying engine variations and mitigation strategies
  - Advanced variation diagnostics
  - Distributed intra-SCR chemistry and performance ***(cf. 2008 Review feedback; 2009 milestone)***
- Pursuing CRADA continuation at Cummins' request