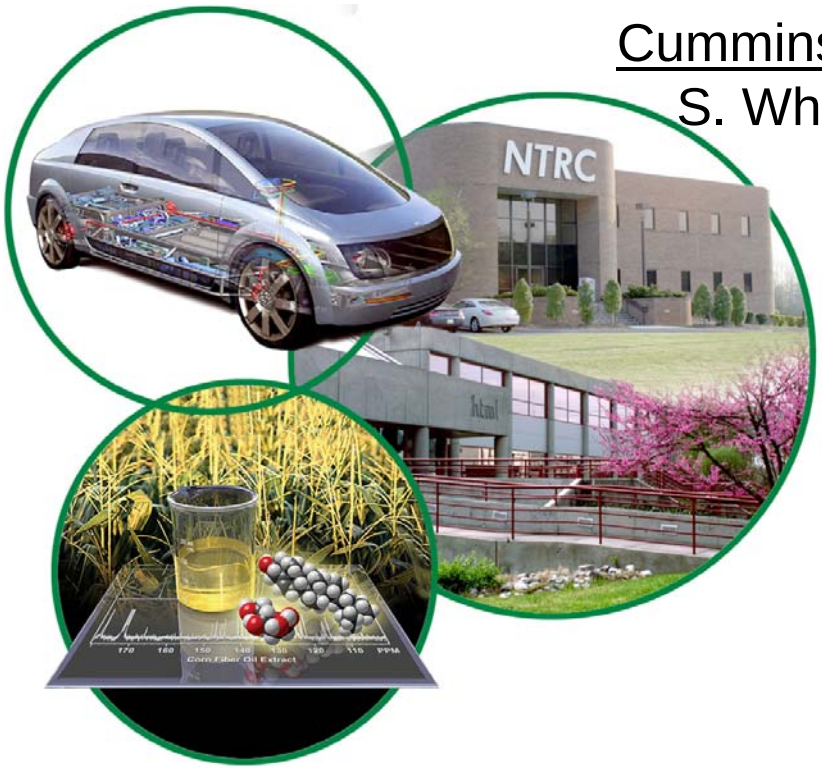
Cummins/ORNL-FEERC CRADA: NOx Control & Measurement Technology for Heavy-Duty Diesel Engines

(Agreement #: 10030)*

Oak Ridge National Laboratory: W.P. Partridge (PI), J.-S. Choi, J. Parks

Cummins Inc.: N. Currier (PI), A. Yezerets, M. Ruth, S. Whitacre, M. Cunningham, K. Kamasamudram

Presenter: Bill Partridge
partridgewp@ornl.gov



Vehicle Technologies Program Annual Merit Review
February 26, 2008, Bethesda, MD

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

This presentation does not contain any proprietary or confidential information.

Purpose of Work

Assist Cummins in addressing barriers
to transportation-market penetration
of fuel-efficient diesel engines

& by doing so
generate useful knowledge
and enable products
with broad public benefit

Major Focus for FY2008:

- Oil Dilution (from engine-managed catalyst regeneration)
- LNT-Catalyst Ammonia Chemistry

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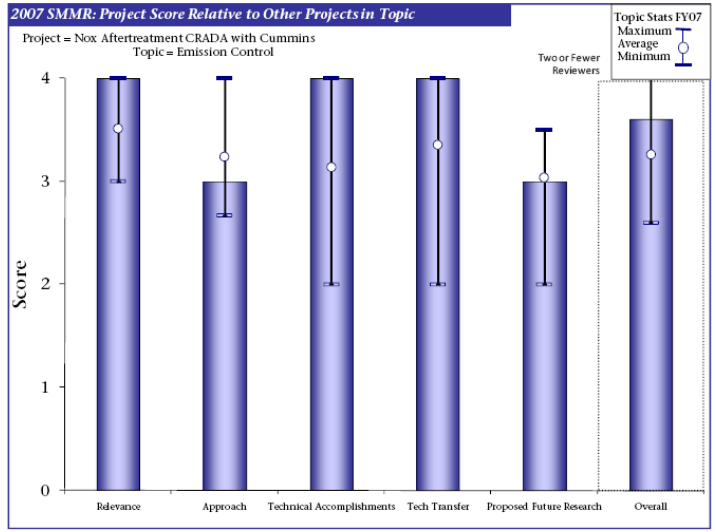
Guidance from FY 2007 Review



- Feedback was very positive
- Highest score achieved in three areas
  - Relevance
  - Technical Accomplishments
  - Tech Transfer
- "A useful industry partnership that has shown good progress and results."
- No weaknesses or recommendations were cited.

- Previous review recommendations:
  - Using fully formulated catalyst *(implemented in '07)*
  - Quantifying H_2S, NH_3, N_2O and SO_2 distributions *(implemented in '07 except NH_3)*
  - ***Major effort in FY2008 to quantify NH_3 chemistry***

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CRADA Addresses Multiple DOE\VT Barriers

Oil Dilution (Engine System Section)

- Can result from emissions control system management and operation
- Oil dilution can cause durability issues
- Conventional methodologies slow development

LNT Ammonia Chemistry (Instrumentation & Bench Section)

- NH_3 must be controlled in viable catalyst systems:
  - Avoid NH_3 slip
  - Manage generation and utilization in LNT and hybrid LNT-SCR systems

Specific DOE\VT Multi-Year Program Plan Barriers Addressed :

- '*Emissions*. The key barriers … incomplete development of aftertreatment technology, especially for NOx;.."
- '*Durability*. .. system has to perform effectively for 120,000 miles…'

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Oil Dilution Research

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Performance Measures – Oil Dilution

Conventional methodologies:

- bottleneck development
- require extractive sampling
- off-line (often off-site) analysis

Performance measures designed to streamline development:

- Fast measurement ~15 min
- On-engine measurements
- Real-time feedback

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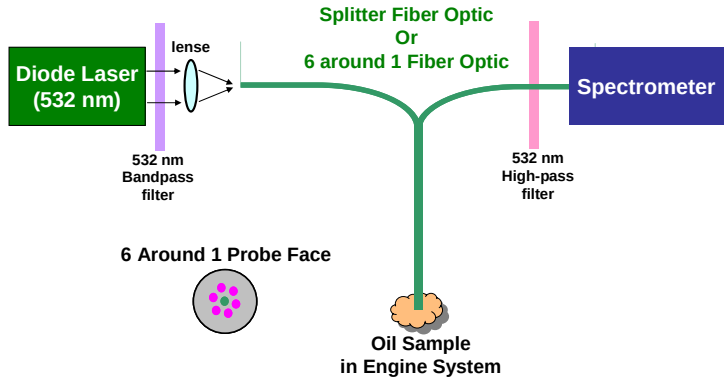
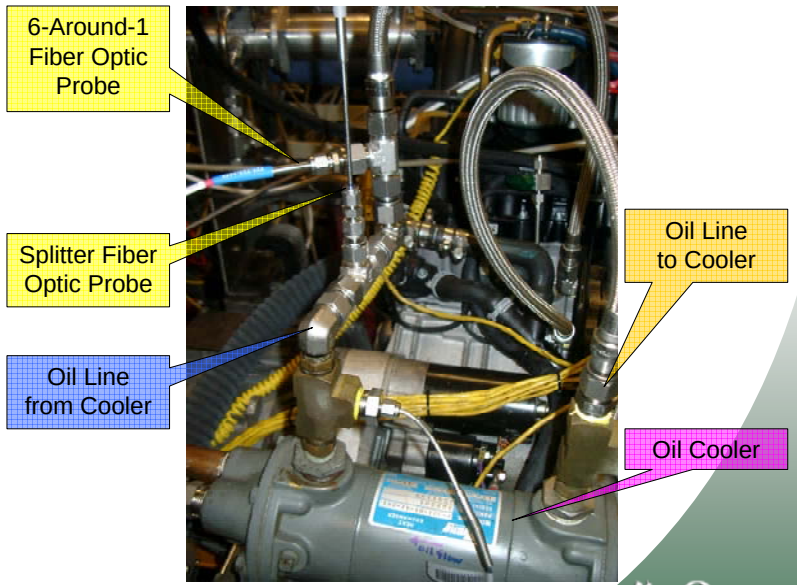
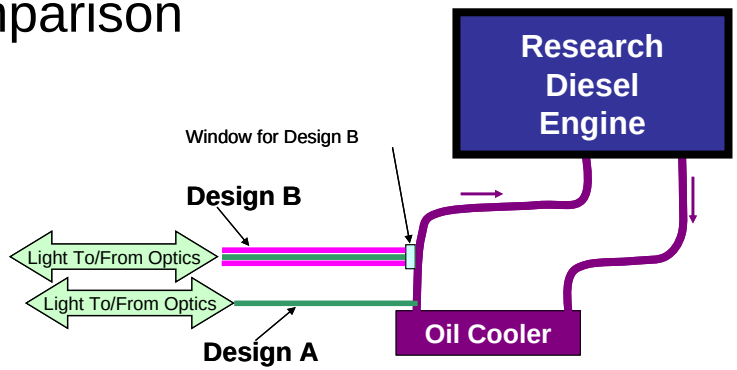
Approach – Oil Dilution

- Inexpensive & compact laser-pointer sources
- Fluorescence of commercial diesel-fuel dye
- Two fiber-based designs implemented
- Sample-point agile optical fiber design
- Engine-cell safe closed system design
- Demonstrate on ORNL research diesel
  - Flexible engine control system
- Extract samples for ASTM method comparison







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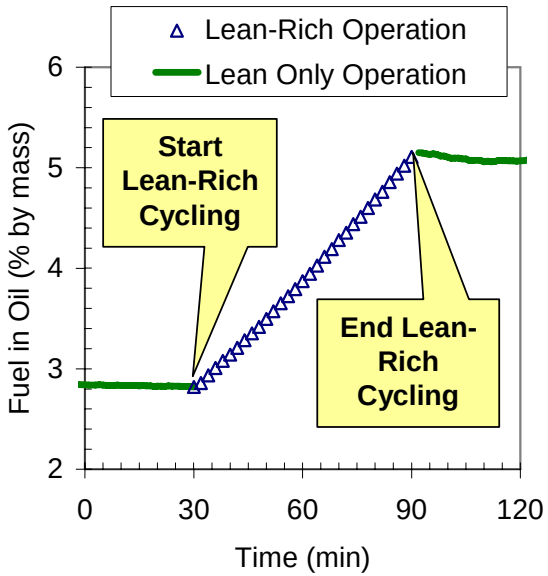
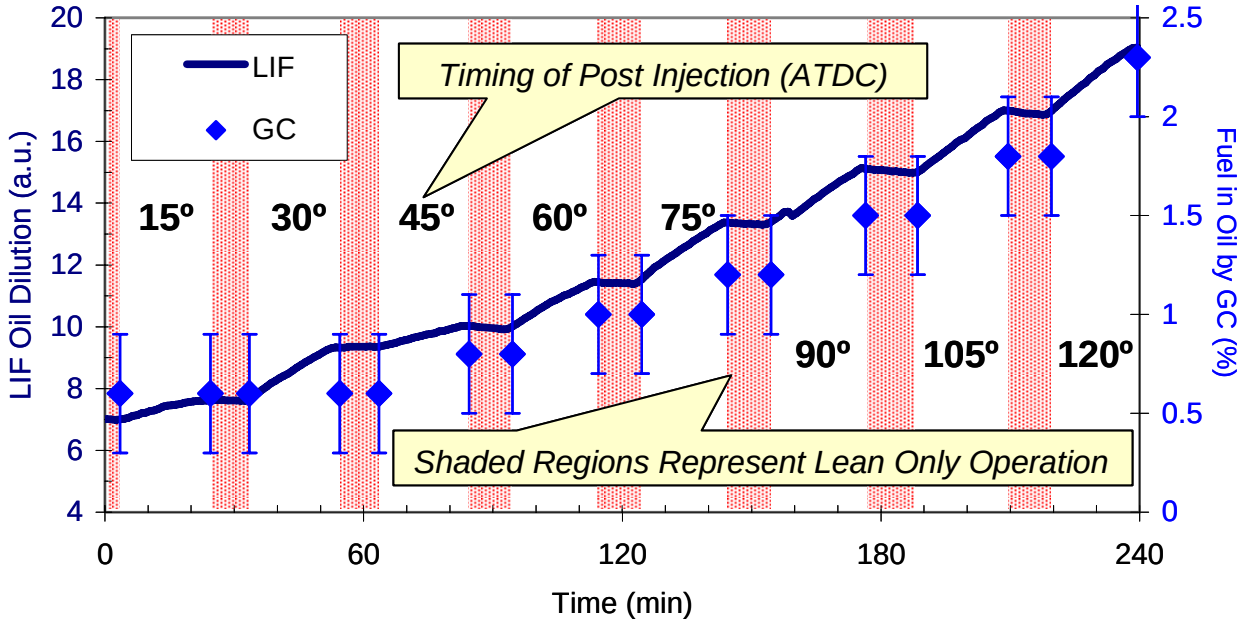
Results – Oil Dilution





- Slope indicates relative oil dilution rate
- Real-time on-engine feedback of oil dilution
  - ~ <15 min feedback time
- Laser-Induced Fluorescence (LIF) method
  - trends with ASTM
  - more sensitive than ASTM
- LIF Oil Dilution diagnostic realizes performance measures

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LNT Ammonia Chemistry Research

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Performance Measures – LNT Ammonia Chemistry

Ammonia is relevant to diesel product development:

- NH_3 slip management
- System design & calibration
- On-board detection of system state
- Cummins development emphasizes fundamental knowledge

Ammonia is difficult to measure w/ SpaciMS:

- Interferences with N_2, H_2O, NOx
- NH_3 is sticky
- Variable and different elution times

Performance Measures address diagnostic and information needs:

- Enable SpaciMS measurement of NH_3 inside operating LNT catalysts
- Map transient NH_3 distribution through catalyst
- Clarify NH_3 formation and utilization in LNT chemistry

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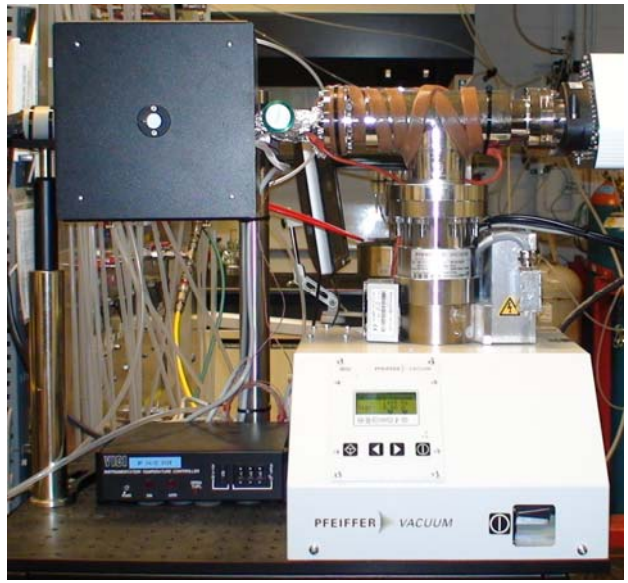
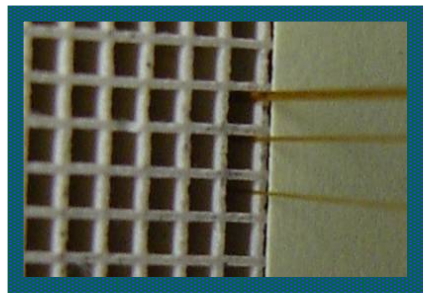
Approach – LNT Ammonia Chemistry

- Catalyst core (3/4” x 3”) on bench reactor
- Washcoat: Pt/Ba/Al_2O_3 model catalyst
  - No cerium – oxygen-storage component
- CLEERS standard short cycling:
  - 60-s lean: 300ppm NO + 10% O_2
  - 5-s rich: 2% H_2
  - Common: 5% H_2O + 5% CO_2 + Ar balance



- ***Resolve species distributions along catalyst channel***
  - SpaciMS
  - NH_3 generation and utilization
  - NOx, N_2 and H_2
- Analyze distributed performance
  - Phase/timing of species puffs
  - Selectivity



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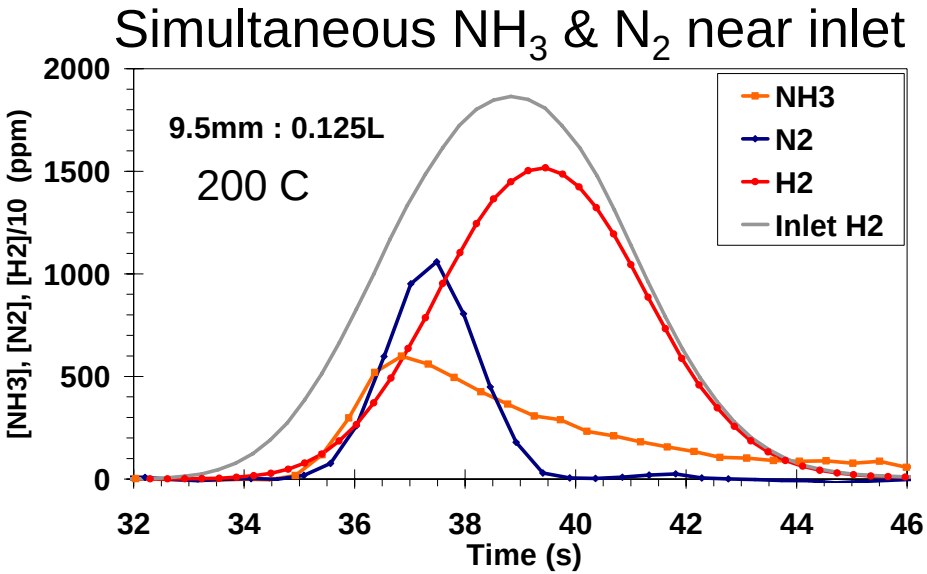
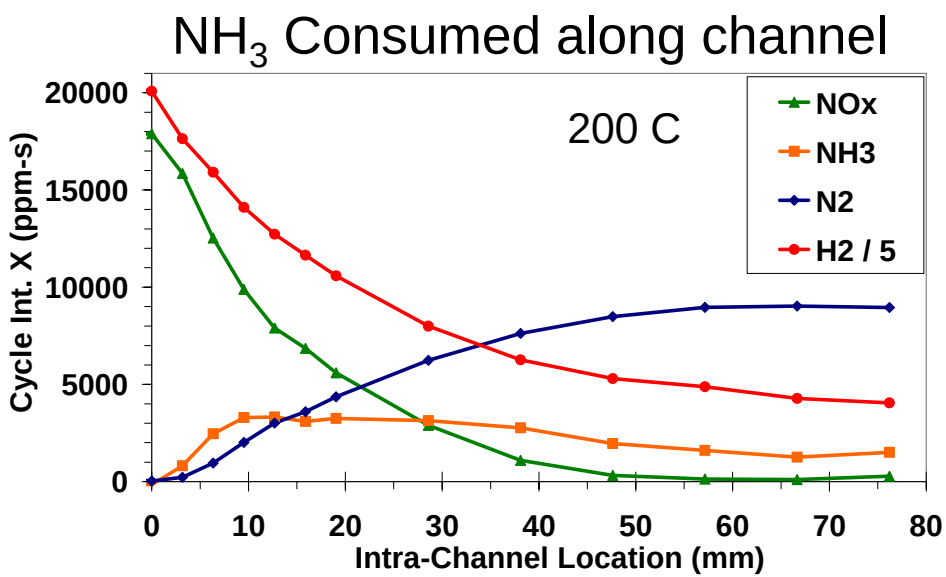
Results – LNT Ammonia Chemistry





- Simultaneous N_2 & NH_3 generation at catalyst front
- NH_3 shifts to later times along catalyst length
- NH_3 consumed along catalyst length along with H_2

SpaciMS NH_3 measurements demonstrated

Must account for NH_3 regeneration role

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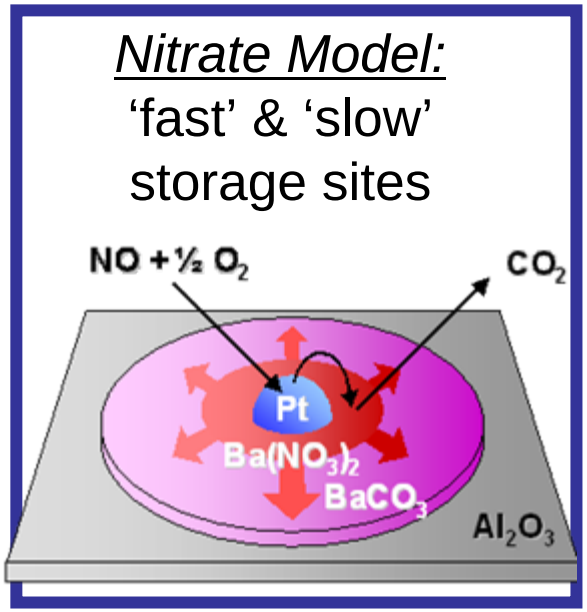
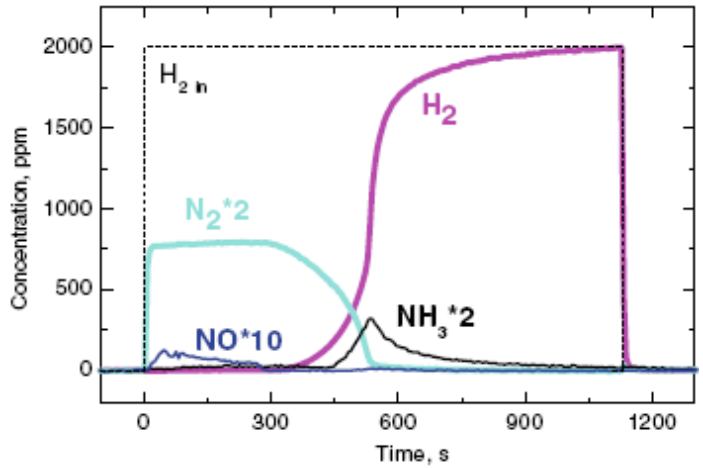
Results – Vis-à-vis Literature Ammonia Chemistry



Dominant Literature NH_3 Theory:

NH_3 created at 'slow' sites, &
NH_3 follows N_2 and reductant slip



Nova et al. (2007) Topics in Catalysis

- Our measurements show same sequence at outlet
- But simultaneous NH_3 and N_2 inside catalyst

NH_3 doesn't always follow N_2

Literature NH_3 model incomplete

NH_3 not always from 'slow' sites

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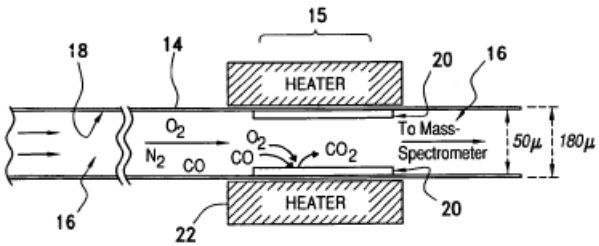
Technology Transfer

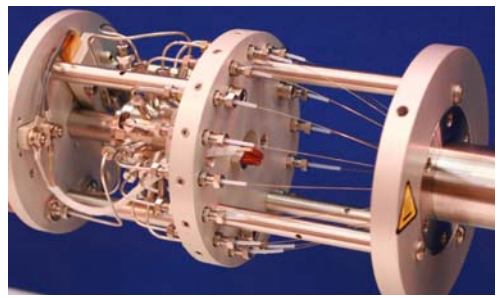
Via CRADA:

- All CRADA activities impact Cummins' product development
- CRADA instrumental in the commercialization of the 2007 Dodge Ram engine-catalyst system

Outside of CRADA:

- Coordination with CLEERS impacts broad range of DOE interests
- Delphi improved reformer-catalyst models based on SpaciMS analysis
- Multiple industry inquiries into Oil Dilution diagnostic
- Hiden Analytical marketing commercial SpaciMS
- 2007 Cummins patent expands SpaciMS capabilities





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Publications, Presentations, Patents

3 Publications:

- **J.-S. Choi, W.P. Partridge, J.A. Pihl, and C.S. Daw, "Sulfur and temperature effects on the spatial distribution of reactions inside a lean NO_x trap and resulting changes in global performance", *Catalysis Today*, doi:10.1016/j.cattod.2008.01.008 (2008).**
- **J.-S. Choi, W.P. Partridge, and C.S. Daw, "Sulfur impact on NO_x storage, oxygen storage and ammonia breakthrough during cyclic lean/rich operation of a commercial lean NO_x trap", *Applied Catalysis B: Environmental* 77, 145-156 (2007).**
- **Jim Parks, Bill Partridge and Shawn Whitacre "Rapid In Situ Measurement of Fuel Dilution of Oil in a Diesel Engine using Laser-Induced Fluorescence Spectroscopy," Society of Automotive Engineers paper 2007-01-4108, 2007.**

4 Presentations:

- **J.-S. Choi, W.P. Partridge, J.A. Pihl, and C.S. Daw, "Sulfur effects on spatiotemporal distribution of reactions in a commercial lean NO_x trap", *AIChE National Meeting*, Salt Lake City, UT, November 4-9, 2007.**
- **Jim Parks, Bill Partridge, and Shawn Whitacre, Rapid In Situ Measurement of Fuel Dilution of Oil in a Diesel Engine Using Laser-Induced Fluorescence Spectroscopy , presented at the SAE Powertrain and Fluid Systems Conference in Chicago, IL on October 29-31, 2007.**
- **J.-S. Choi, W.P. Partridge, and C.S. Daw, "Assessing a commercial lean NO_x trap performance via spatiotemporal species profile measurements", *North American Meeting (NAM) of the North American Catalysis Society*, Houston, TX, June 17-22, 2007.**
- **W.P. Partridge, J.-S. Choi, C.S. Daw "Distributed Impact of Sulfation on LNT Catalyst Reactions," 10th DOE Crosscut Workshop on Lean Emissions Reduction Simulation, University of Michigan, Dearborn, Michigan, May 2nd, 2007.**

1 Patent:

- **N.W. Currier, A. Yezerets, US Patent Number US 7,211,793 B2, Mass Spectrometry System and Method, May 1, 2007.**

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Future Activities

Engine-Systems Section:

- Apply oil-dilution diagnostic on development V engine at Cummins (scheduled - March 2008)
- Develop and apply methods to quantify cylinder and cycle dispersion

Instrumentation & Bench Section:

- Characterize NH_3 chemistry in LNT with oxygen-storage component (Umicore, CLEERS reference catalyst)
- Characterize sulfation impact on LNT catalyst reactions, including NH_3 formation and utilization and water-gas-shift

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Summary

- **Relevance to DOE Objectives**
  - Reduce fuel consumption by enabling diesel market penetration
- **Approach**
  - Real-time on-engine measurement of oil dilution
  - Measure evolution of NH_3 generation and utilization inside catalyst
- **Technical Accomplishments**
  - Streamline engine calibration
  - Enable SpaciMS NH_3 measurements & clarify LNT catalyst reactions
  - Enable improved modeling of LNT and hybrid LNT-SCR systems
- **Technology Transfer**
  - Broad based transfer via Cummins products & outside CRADA
- **Future Plans**
  - Measure cylinder and cycle dispersion on development engines
  - Quantify distributed impact of sulfation on NH_3 LNT reactions
  - Designed to address Cummins' technical barriers

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