Efficient Emissions Control for Multi-Mode Lean DI Engines

Presented by **Jim Parks (PI)**

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OAK RIDGE NATIONAL LABORATORY
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Overview

- Timeline
  - » Start: FY2007
  - » Finish: Ongoing
  - » % Complete:
- Budget
  - » FY08 Funding: $200k
  - » FY09 Funding: $200k
  - » FY10 Funding: $200k
  - » FY11 Funding: $200k

- Barriers
  - » Emissions regulations for advanced lean engine market penetration
    - "An insufficient knowledge base will inhibit the development of advanced LTC or mixed-mode combustion systems…."
    - "Meeting EPA requirements … with little or no fuel economy penalty will be a key factor for market entry …."
- Partners
  - » Catalyst Suppliers
    - Manufacturers of Emissions Controls Association (MECA)
    - Nanostellar
  - » CLEERS
  - » Other ORNL Projects:
    - Advanced Combustion
    - Joule Milestone
    - Health Impacts

Objectives

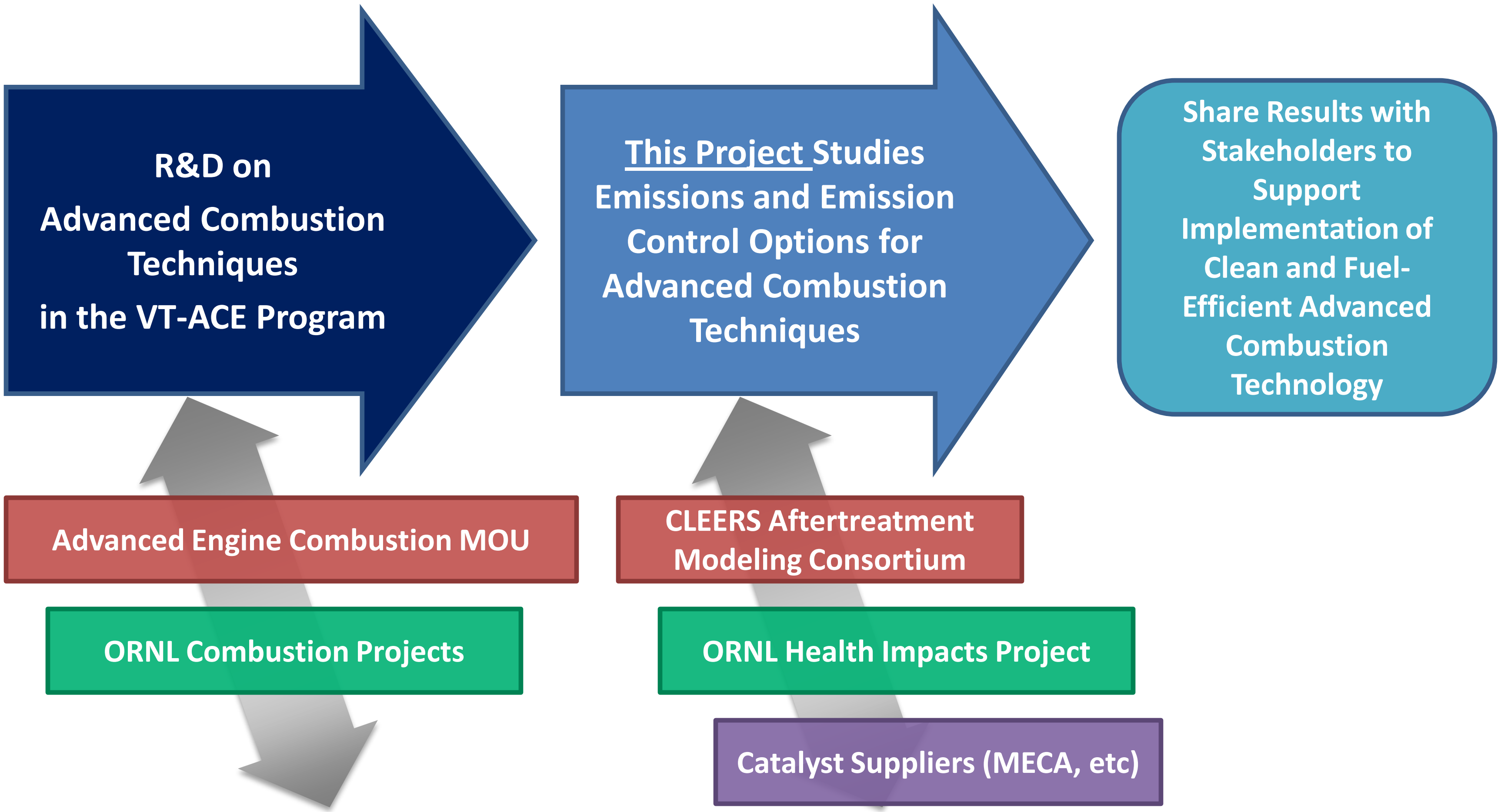
- **Enable efficient lean engine market penetration by meeting emission regulations with efficient, cost effective aftertreatment**
  - » Characterize emissions from ***advanced engine combustion modes*** and define the synergies or incompatibilities with emissions control technologies
    - LNT, Urea SCR, HC-SCR, Lean NOx Catalysis, DPF, Oxidation
  - » Study effect of ***multimode*** operation on system performance
  - » Minimize fuel penalty for regeneration
  - » Develop stronger link between bench and full-scale system evaluations
  - » Interact in CLEERS consortium to respond to industry needs and support model development

Milestones

- **FY10:**
  - » Comparison of Cu- and Fe-zeolite Urea-SCR catalyst performance for multimode diesel engine operation. (September 30, 2010)
  - » Status: Complete (Ongoing work continuing)
- **FY11:**
  - » Characterization of hydrocarbon oxidation efficiency of diesel oxidation catalyst for low load operation with advanced combustion which results in lower exhaust temperatures (September 30, 2011).
  - » Status: Complete (Ongoing work continuing)

Approach/Strategy

- **Take advanced combustion techniques and study emissions issues and emission control technologies for “multi-mode” (advanced + conventional) combustion**



Note: DOE-supported Combustion MOU and CLEERS consortiums include industry, national labs , and universities

Technical Accomplishments and Progress

Since last review (June 2010):

- **Studied emissions from RCCI (Reactivity Controlled Compression Ignition) combustion approach (via ORNL combustion team and Reitz et al. at University of Wisconsin)**
  - » Oxidation catalyst studies at operating point demonstrated before last Merit Review
- **Evaluated Nanostellar diesel oxidation catalysts under PCCI (Premixed Charge Compression Ignition) operating conditions**
  - » Focus on light-off at low exhaust temperatures created by efficient combustion
- **Conducted Urea-SCR experiments with Multimode operation including PCCI**
  - » Focus on hydrocarbon fouling of Cu- and Fe-zeolites

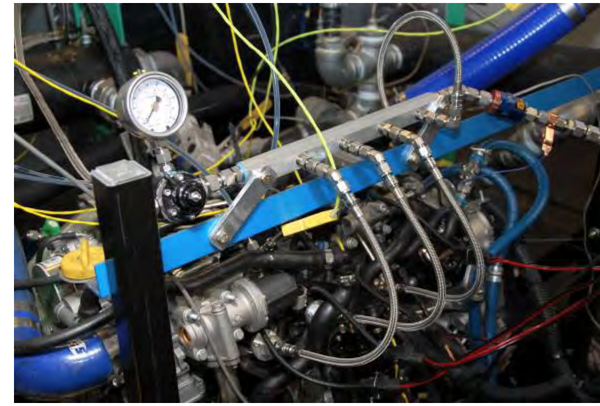
Engine Platform:

GM 1.9-l, 4-cyl diesel engine

- *High-pressure common rail*
- *Full-pass Drivven control system (up to 5 injection events)*
- *Variable geometry turbocharger*
- *Cooled EGR*
- *Swirl actuation*

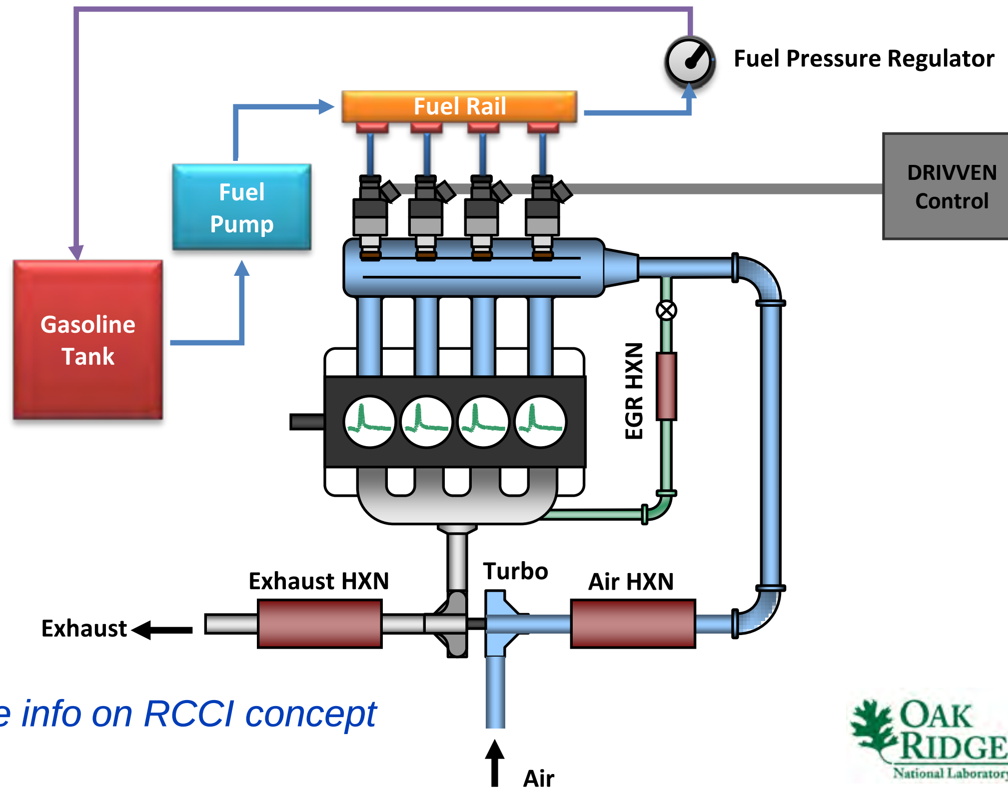
Technical Accomplishments: RCCI Emissions

- **Last year, RCCI (“dual-fuel”) approach from Univ. of Wisconsin (UW) demonstrated on ORNL multi-cylinder engine**
  - » +1.5% efficiency (η_T) and low NOx demonstrated
- **ORNL collaborating with UW to compare UW model to ORNL multi-cylinder experimental results** ***[See Briggs talk for more info]***
- **Efforts continuing in this area**
  - » DOC effects on emissions presented here



2300 rpm, 4.2 bar BMEP condition (no EGR)

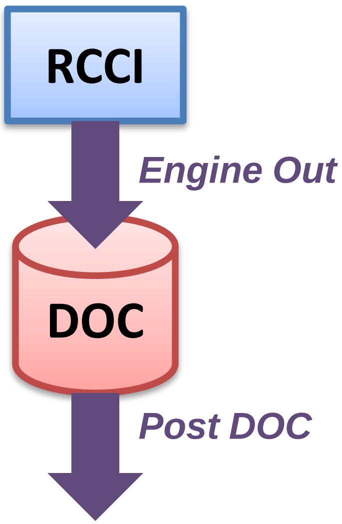
	Conventional Diesel	**RCCI (77% Gasoline)**
BTE (%)	32.1	33.6
NOx (ppm)	94	7.5
FSN	1.78	0.02
CO (ppm)	423	1512
HC (ppm)	296	2581
Exhaust T (C)	412	260



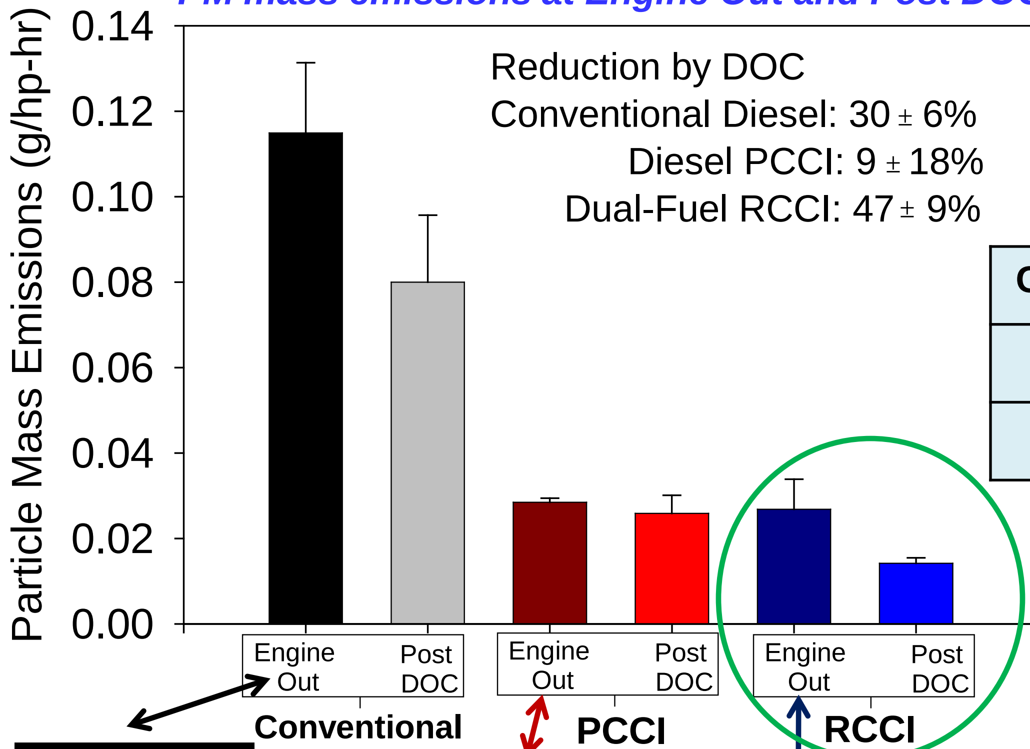
See Kokjohn et al. SAE 2009-01-2647 for more info on RCCI concept

Interesting PM results raised questions for investigation

- **RCCI particulate matter (PM) found to be very different from conventional and PCCI PM**
- **PM filter images and size distribution data suggested high organic content in PM from RCCI**
- **DOC reduces RCCI PM mass significantly**



PM mass emissions at Engine Out and Post DOC



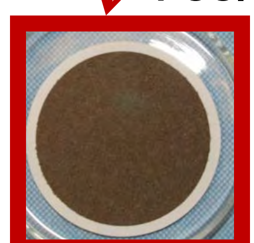
Exhaust Temperature

Conventional	415ºC
PCCI	420ºC
RCCI	250ºC

DOC effective for RCCI PM even though exhaust temperature lower

PM filter samples at Engine Out

Conventional

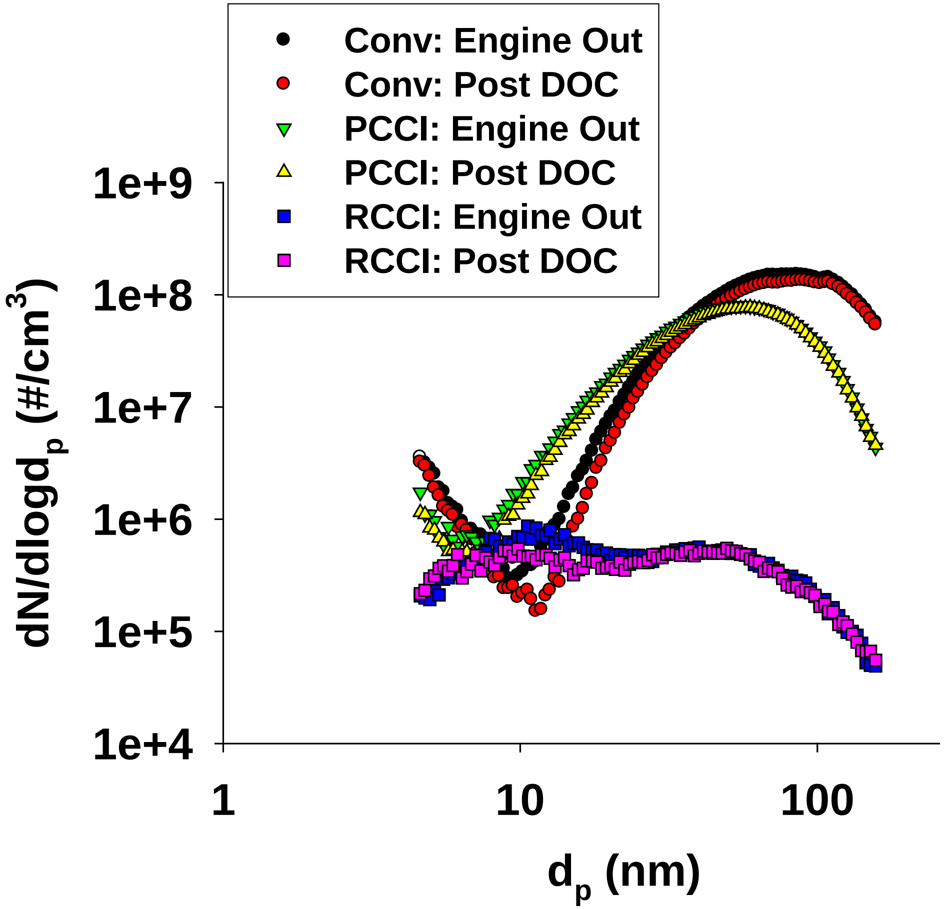


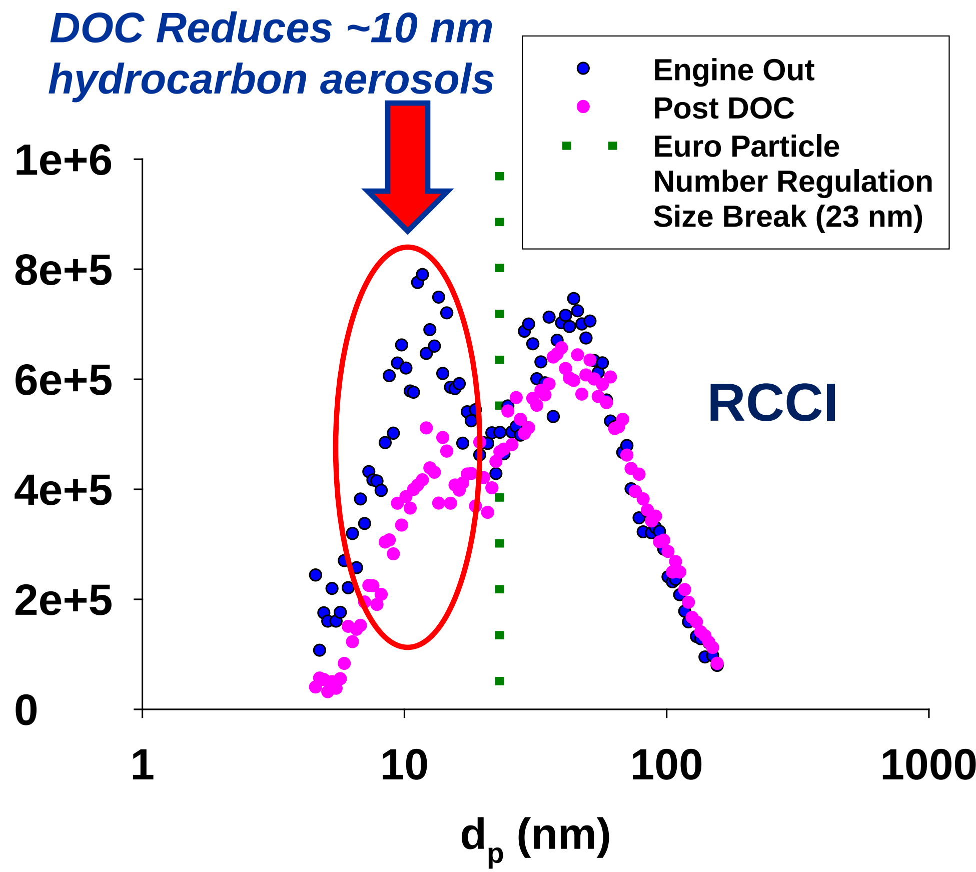
PCCI

RCCI

DOC Specifically Reduces 10 nm Aerosol Particles

- **Scanning Mobility Particle Sizer (SMPS) shows PM size distribution differs for conventional, PCCI, and RCCI particulate**
- **RCCI PM has bimodal distribution**
- **DOC effective at reducing RCCI PM in ~10 nm range but not ~60 nm range**





Note: log y-axis for plot on left but linear y-axis for plot on right

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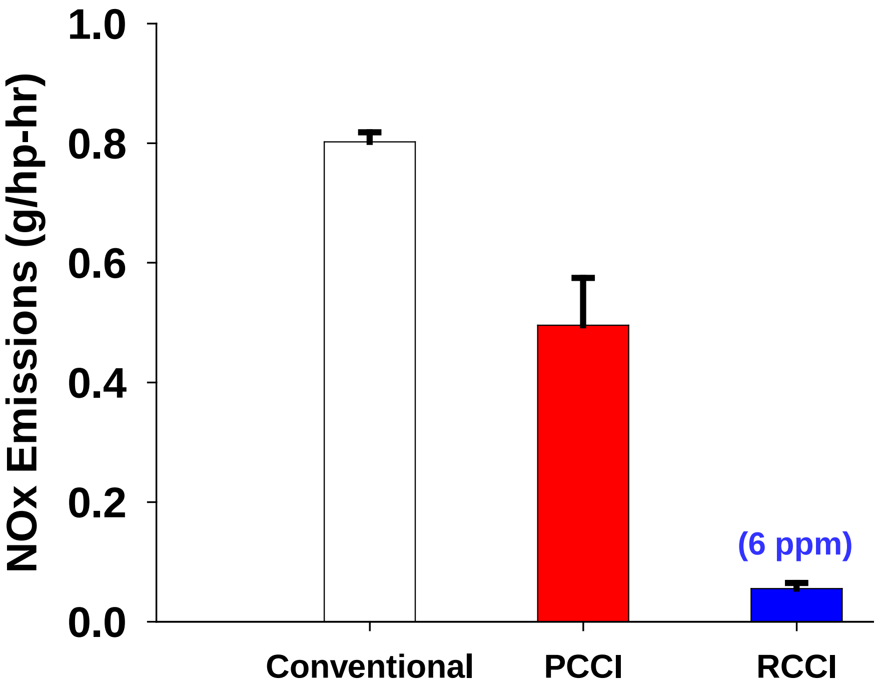
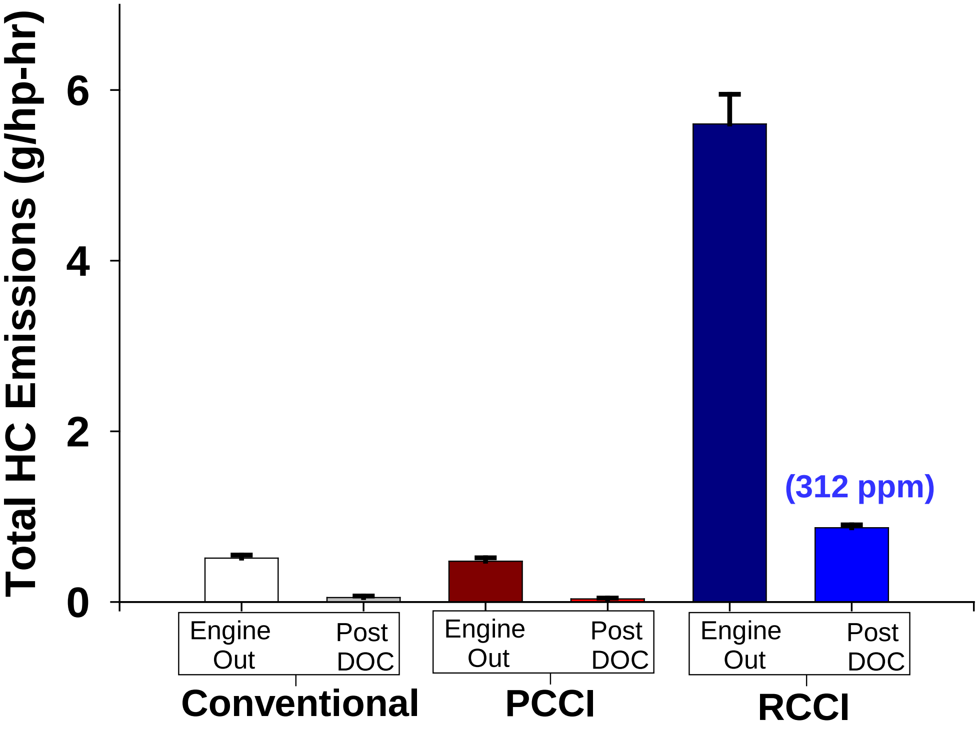
Interim Summary: RCCI + DOC Gives Low Emissions



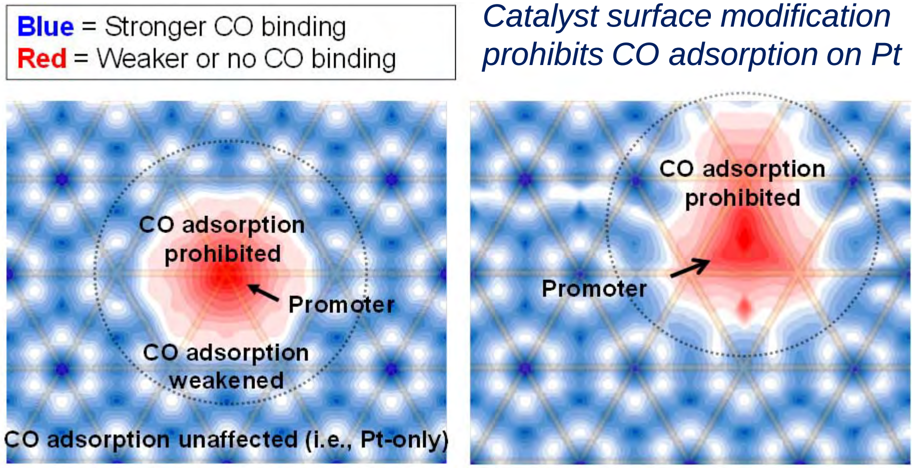


- **RCCI PM has high organic content and small size indicative of hydrocarbon-heavy aerosols**
- **DOC found to be effective in reducing PM emissions and hydrocarbon emissions from RCCI**
- **Resulting RCCI tailpipe emissions are very low for NOx without NOx catalyst**

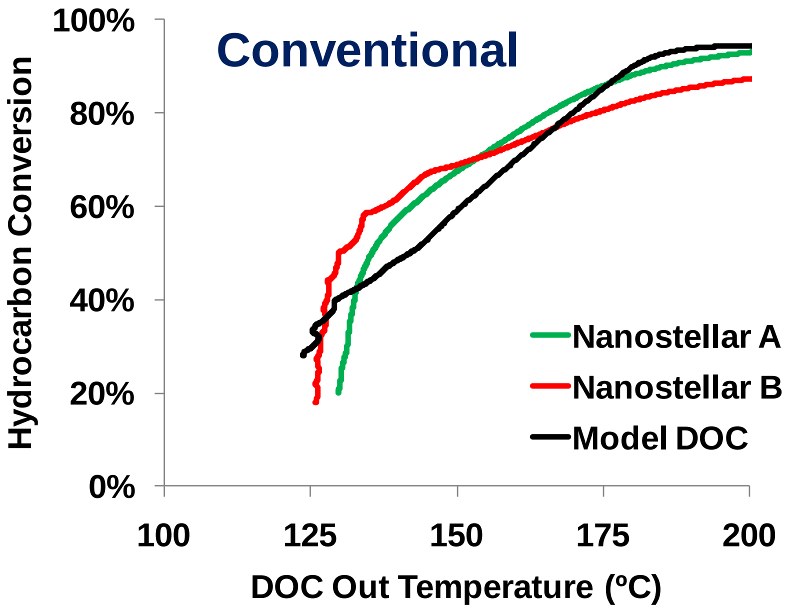
RCCI is fuel-efficient with emissions that can largely be controlled with DOC alone thus reducing the fuel penalty and cost of the aftertreatment system

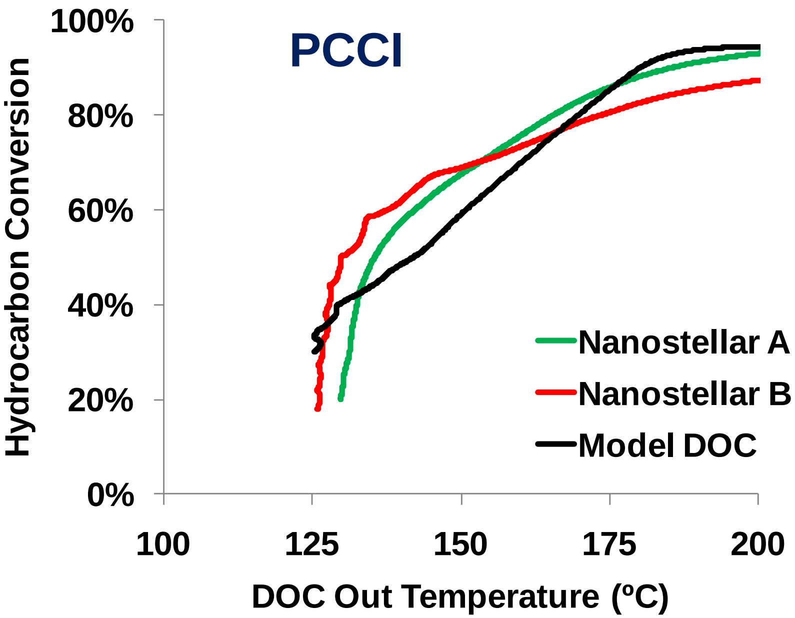
Technical Accomplishments: Nanostellar DOC Studied for Low Temperature Emission Control from PCCI

- **Diesel Oxidation Catalysts (DOCs) from Nanostellar studied with Premixed Charge Compression Ignition (PCCI)**
  - » Nanostellar approach is to mitigate CO fouling of DOC site activity for HC oxidation
  - » See SAE 2008-01-0070 Fujdala et.al. for more details
- **Engine-based experiments with conventional and PCCI combustion**
  - » Comparisons made to model DOC (100 g/ft^3 Pt on Al_2O_3)



Above figure supplied by Nanostellar



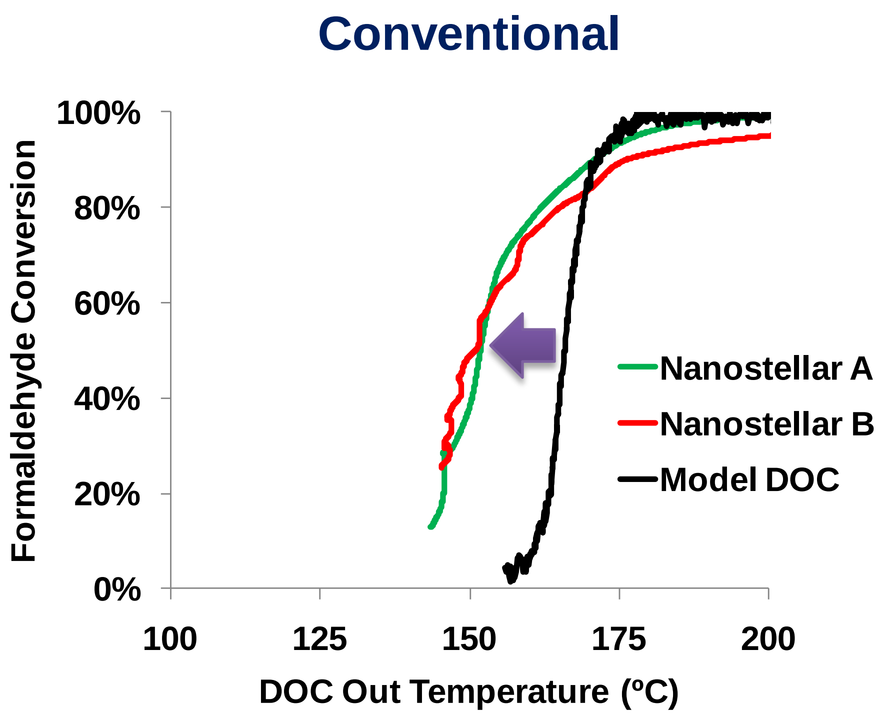


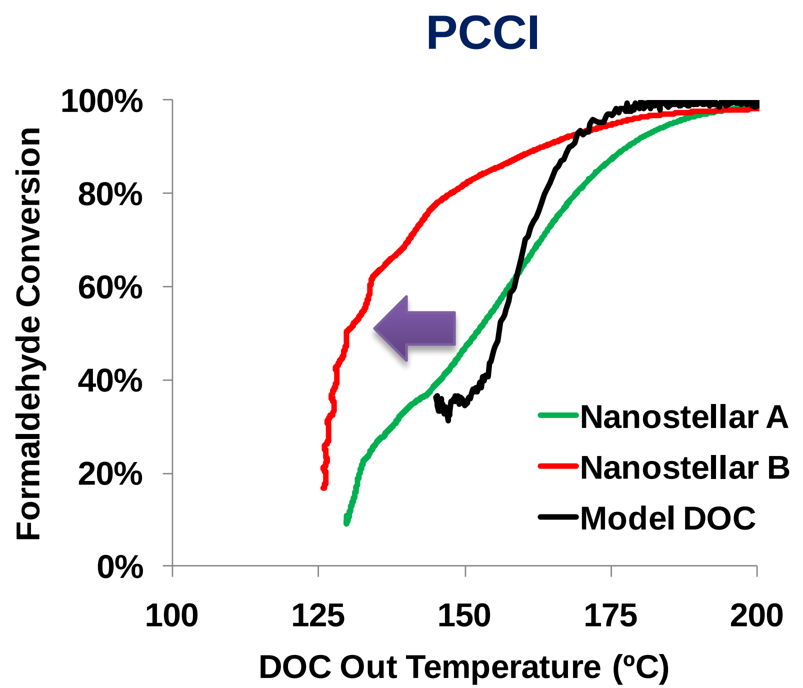
Engine Condition: 1500 rpm, 1.0 bar

Lower Light-off for Formaldehyde Oxidation Observed with Nanostellar DOCs with Some Dependence on Formulation

- **15-20ºC drop in light-off temperature for formaldehyde oxidation observed with Nanostellar DOCs vs. model DOC**
  - » Higher level of formaldehyde from PCCI shows differing results between two Nanostellar formulations
- **CO oxidation efficiency results also lower light-off for Nanostellar DOCs**

Note: PCCI Formaldehyde emissions are 2x Conventional



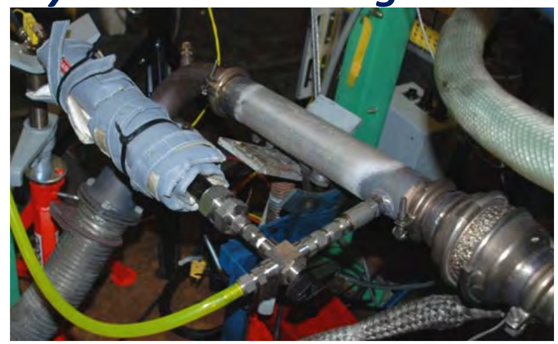


Engine Condition: 1500 rpm, 1.0 bar

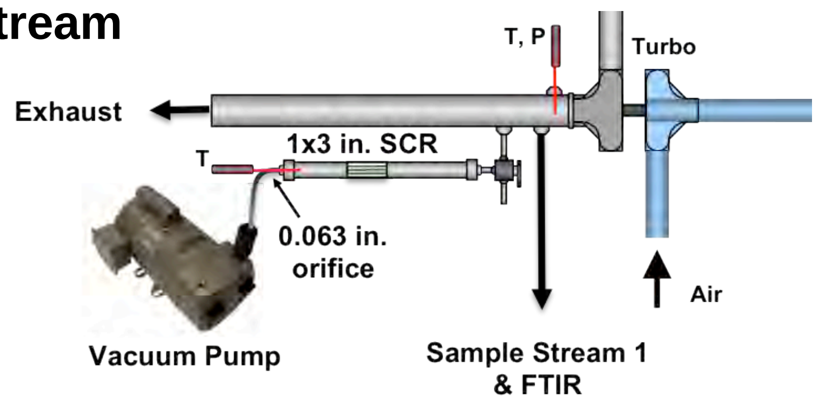
Technical Accomplishments: HC fouling of Zeolite SCR catalysts examined at low temperatures with efficient PCCI

- **First, catalyst cores exposed to engine exhaust from conventional and PCCI combustion on slipstream setup (3 hr exposure)**
  - » Ford Cu zeolite
  - » Umicore Fe zeolite (CLEERS ref)
- **After exposure, SCR performance characterized on bench flow reactor**
  - » Fouling impacts measured before and after temperature ramp (oxidizing conditions)
- ***Aggressive*** **conditions: 115ºC, 30k/hr SV, no DOC/DPF upstream**

Catalysts Fouled in Engine Exhaust



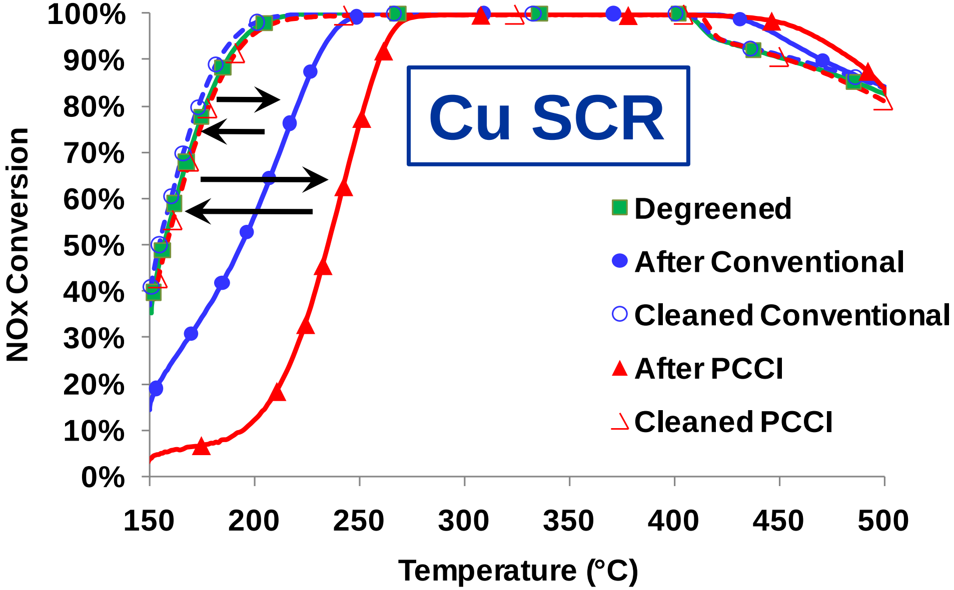
Performance Studied on Bench Reactor



Schematic of engine exhaust slipstream for catalyst exposure to hydrocarbons

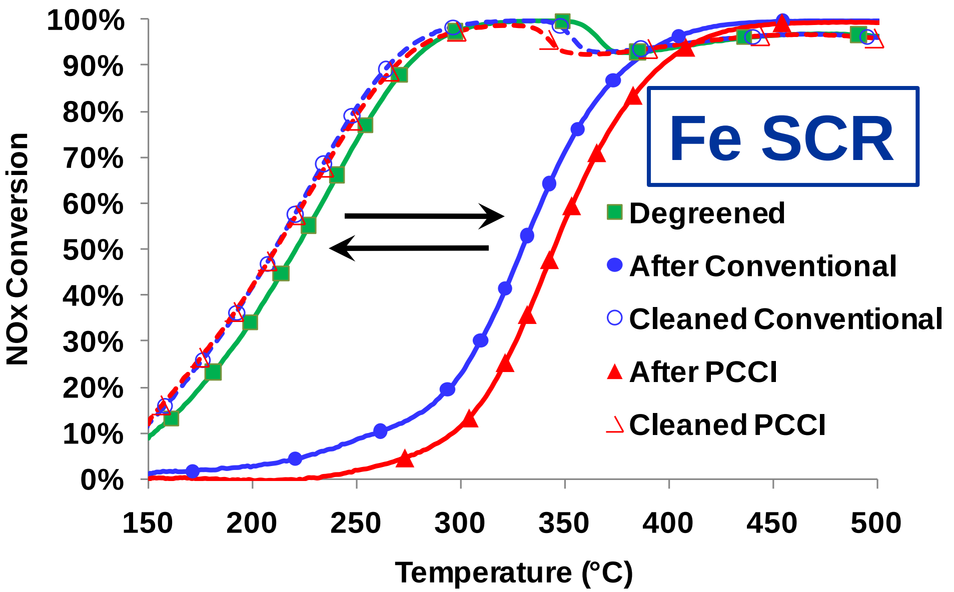
Cu-zeolite shows more tolerance to HC fouling (vs. Fe-), but fouling from PCCI HCs more severe (for Cu- case)

- **HC/soot fouling impacts mainly low temperature NOx conversion**
  - Fe much worse than Cu as expected
  - PCCI and Conventional similar for Fe
  - PCCI worse than Conventional for Cu
- **Performance loss reversible via higher temperature exposure (see "Cleaned" data plots)**



Engine Condition: 1500 rpm, 2.6 bar BMEP

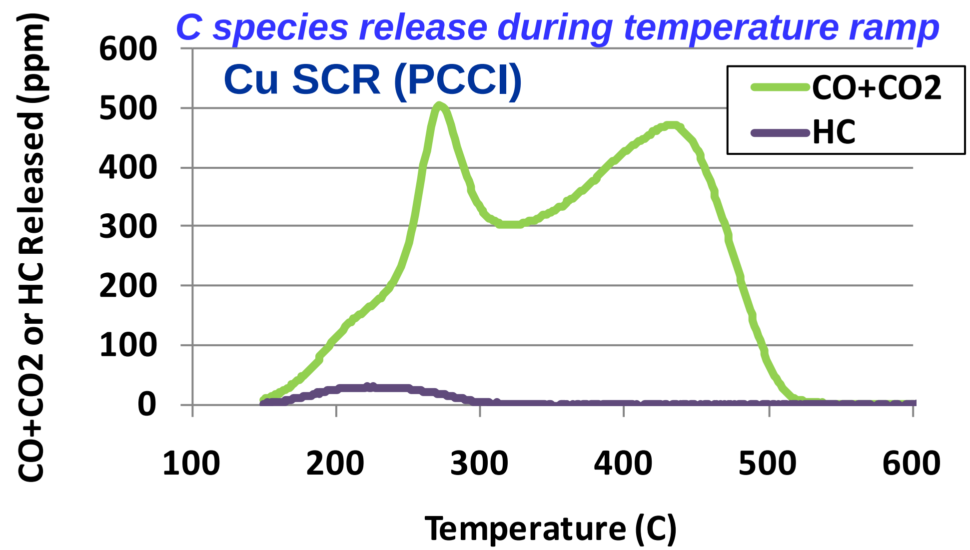
	Conventional	PCCI
Engine Out NOx	1.02 g/bhp-hr	0.24 g/bhp-hr
Engine Out HC	1.35 g/bhp-hr	2.19 g/bhp-hr
Engine Out CO	3.12 g/bhp-hr	11.70 g/bhp-hr

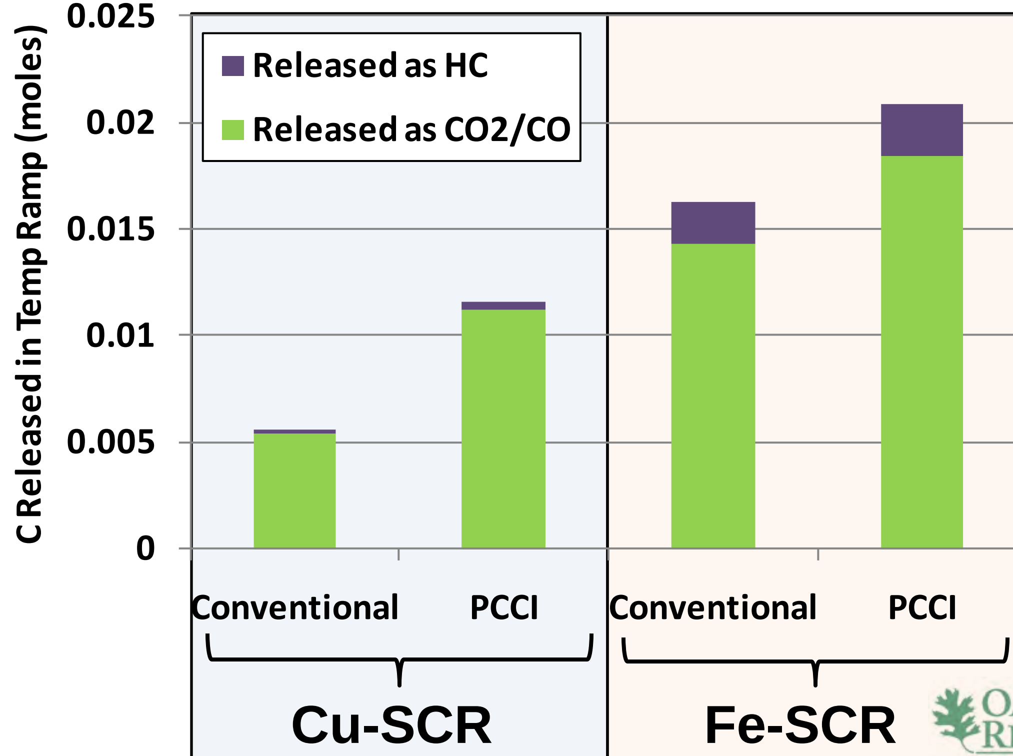


Bench Flow Reactor Conditions:
Inlet: 350 ppm NOx + 350 ppm NH_3 (ANR=1)
SV=30k/hr, 14% O_2, 4.5% H_2O

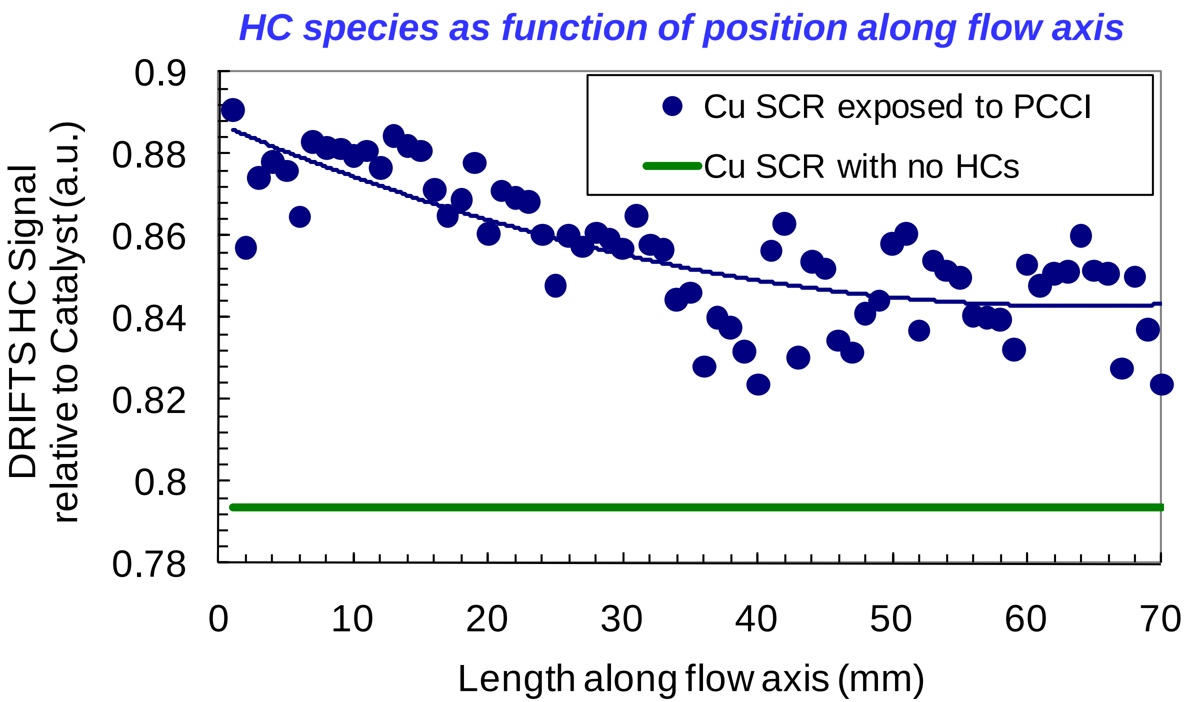
Oxidation and Release of HCs differs for Cu- and Fe-SCR

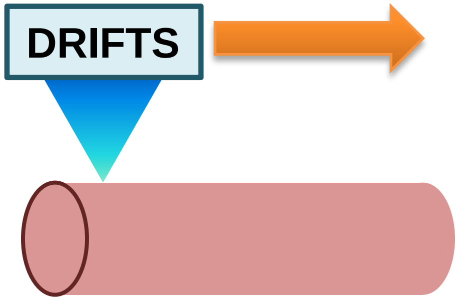
- **During temperature ramp, HCs, CO, and CO_2 are released by SCR catalysts**
- **Integrated results for total moles of HC and CO+CO_2 show differences in catalysts**
  - » More total C trapped on Fe-zeolite
  - » More total C trapped during PCCI (vs. Conventional)
- **For Cu-SCR, 2x more C released from PCCI exposure (vs. Conventional)**
  - » Note that PCCI has higher HC emissions (same exposure time)
  - » C release results consistent with NOx performance results





Interim Summary: Reversible HC Fouling Observed (Analysis of Specific HC Chemistry In Progress)





- **DRIFTS detects HC variation along length of catalyst**
- **Further investigations of HC chemistry in progress with Gas Chromatography**

DRIFTS = Diffuse Reflectance Infrared Fourier Transform Spectroscopy

- **Higher HCs from PCCI increases fouling of Cu SCR, but effect reversible**
- **Results will be shared at:**
  - » CLEERS workshop
  - » North American Catalysis Society Meeting (NAM)
  - » ASME Internal Combustion Engine Division 2011 Fall Technical Conference
    - publicizing work here instead of Fall SAE Powertrain, Fuels, and Lubricants Conference

Collaborations

- **Engine/Combustion**
  - » Working internally with ORNL combustion team which in turn works externally with Combustion MOU and Univ. of Wisconsin
    - Combustion experience for PCCI and RCCI ported into this project
  - » GM 1.9-liter platform used widely in research community
- **Emissions and Catalysts**
  - » CLEERS
  - » Conducted studies with catalysts from MECA and Nanostellar (since last Merit Review)
  - » Commercial Cu-based SCR from Ford product for hydrocarbon fouling studies
  - » In previous years, worked with AirFlow Catalysts (DOC) and Filter Sensing Technologies (RF sensor)

Future Work

- **Remainder of FY2011**
  - » Continue work related to oxidation catalyst control of emissions from RCCI combustion
    - ORNL combustion team is working with Univ. of Wis. on demonstrating other operating points on multi-cylinder engine
  - » Continue to examine affect of hydrocarbons from PCCI on urea-SCR catalyst
    - Further definition of hydrocarbon species effects
    - Compare engine combustion specific hydrocarbon chemistry effects to synthetic hydrocarbon bench studies (at ORNL and PNNL)

- **Beyond**
  - » Investigate lower pressure drop DPF systems that can be enabled by PCCI
    - » intent would be to examine fuel benefit of delta P reduction

Summary

Technology	Findings	Implications
RCCI with DOC	PM is largely small dia. HC aerosols which DOC can oxidize	Reduced fuel penalty and reduced size/cost for aftertreatment
PCCI with DOC	Less CO adsorption on DOC leads to lower light-off temperature for HCs (vs. model DOC)	Some improvement in DOC HC/Formaldehyde control for advanced combustion (more needed)
PCCI with SCR (Cu vs. Fe)	Newer Cu-SCR shows better resistance to HC fouling; fouling is reversible even for higher HCs from PCCI	Cu-SCR enables more fuel efficient combustion, but on-board HC removal likely required

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