Cummins-ORNL\FEERC Combustion CRADA: Characterization & Reduction of Combustion Variations

W.P. Partridge (PI), J. Yoo, D.A. Splitter, J.P. Szybist,
V. Prikhodko, R. S.-Gonzalez, R.M. Connatser, J.E. Parks
Oak Ridge National Laboratory

S.C. Geckler (PI), A. Perfetto, R.A. Booth, D.E. Koeberlein,
K. Augustin, S.-m. Moon, S.S. Popuri, F. Tao, L.E. Kocher
Cummins Inc.

Project ID:
ACE077

Presenter: Bill Partridge
partridgewp@ornl.gov

2014 DOE Vehicle Technologies Program
Annual Merit Review
June 18, 2014, Arlington, Virginia

U.S. DOE Program Management Team:
Gurpreet Singh, Ken Howden, Leo Breton

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

- New SOW start: Sept. 2012
- Current end date: Sept. 2015
- ~53% Complete

Budget

- 1:1 DOE:Cummins cost share
- DOE Funding:
  - FY2012: $300k
  - FY2013: $300k
  - FY2014: $300k

Barriers

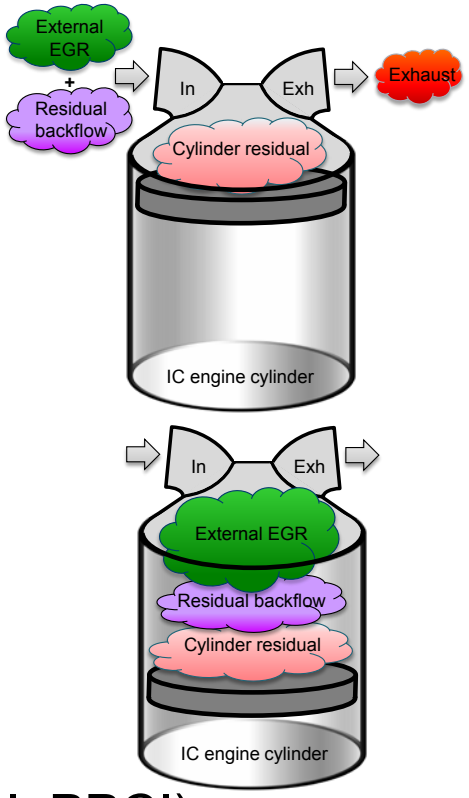
- *Engine combustion*
  - Intake-charge uniformity
  - Combustion uniformity
  - Incomplete combustion
- *Engine controls*
  - Variability & diagnostics
  - Lower-penalty control methods
  - Diagnostics for demonstration of improved efficiency control methods
- *Durability*
  - Combustion instabilities
  - Corrosion, erosion etc. from nonuniformity induced condensation

Partners

- ORNL & Cummins Inc.
- Cummins HD SuperTruck project

Objectives & Relevance

Understand Nature of Cylinder Charge Fluctuations
to Accelerate Development
of Advanced Efficiency Engine Systems



Objectives

- Assess fluctuations in cylinder-charge components
  - Internal EGR (residual & rebreathed residual-backflow)
  - External EGR & intake air
- Apply insights to advance development
  - Validate & tune 1-D & 3-D design models
  - Assess specific hardware & architectures
  - Assess control strategies

Relevance – Charge Uniformity impacts:

- Combustion uniformity
- Performance of advanced-combustion strategies (RCCI, PPCI)
- Required engineering margins (efficiency penalty, fuel economy)
- Durability & ultimate efficiency limits across all cylinders

Milestones

2013 Milestones:

- Apply EGR Probe to assess:
  - ✓ Spatiotemporal performance of advanced intake architectures,
  - ✓ Performance of numerical-simulation design tools used for development
- Follow-on campaign at Cummins to assess design modification
  - Canceled due to budget sequester
  - ✓ Alternate engine work at ORNL to forward CRADA goals
- Improve EGR Probe based on campaign findings:
  - ✓ Resolved probe-to-probe variations

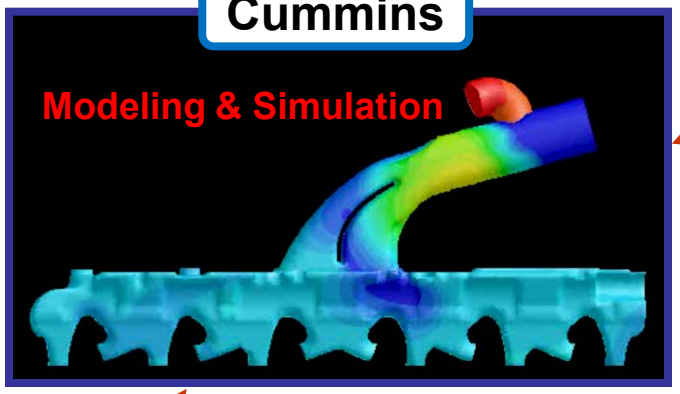
2014 Milestone (on schedule for timely completion):

- ✓ Specify second laser for quantifying intake & residual-backflow CO_2 **(Q1)**
  - i.e., external & internal EGR
- ✓ Assess methods for differentiating intake and residual-backflow CO_2. **(Q2)**
  - Measure H_2O, Temperature & CO_2
- Bench-level demonstrate of method for CO_2 differentiation. **(Q3)**
- Method assessment for measuring cylinder-residual variations. **(Q4)**

Global Approach for Improving Energy Security

Develop & apply advanced diagnostics for engine-system characterization to enable: *model validation, hardware development & controls for fuel-efficient engines*

Cummins



Cummins & ORNL

Components, Methods, Systems & Prototypes Assessment

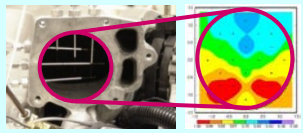
Model Validation

System Studies

ORNL

Diagnostics Development & Applications

- Fast intake & exhaust handling
- In-cylinder residual fraction
- Fueling variations & dilution



Cummins

Controls Development

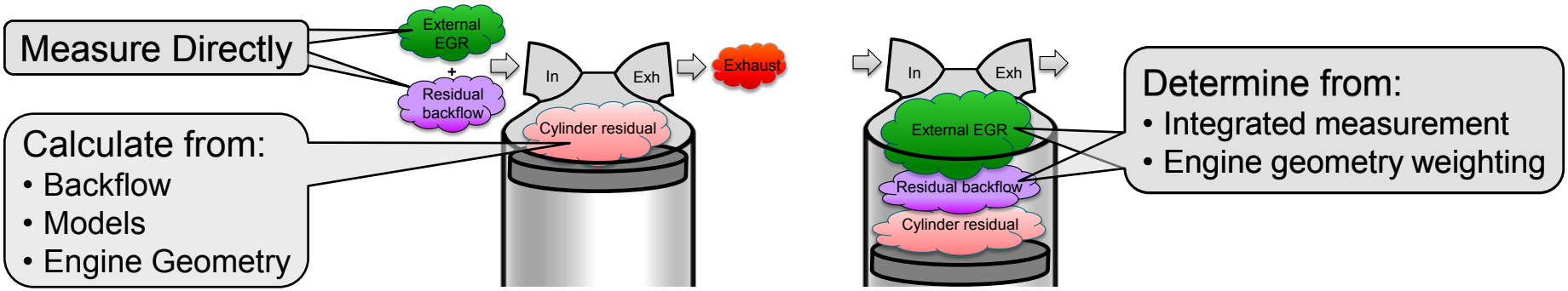
Clean, Fuel-Efficient, Durable

Engines in the Marketplace

Cummins 2007 6.7L ISB

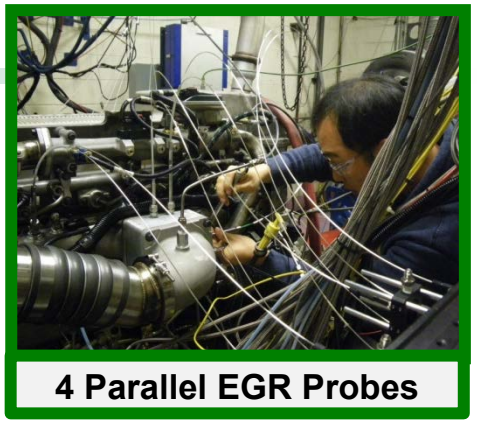
Detailed Approach for 2014 Objectives

Develop & Apply Advanced Diagnostics to Characterize Cylinder-Charge Variations



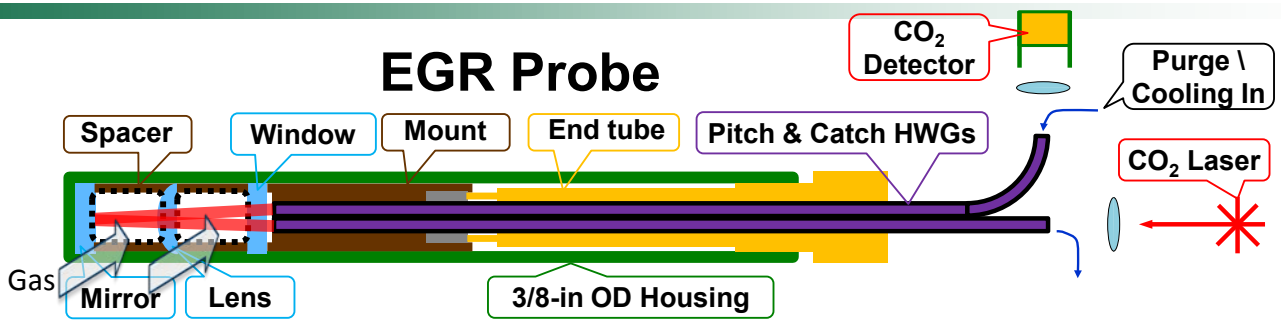
- Develop diagnostic to directly characterize backflow & external EGR-Air
  - CO_2, H_2O, Temperature
- Develop procedure to determine net-charge nature from components
  - Directly measure residual backflow & external-EGR-Air
  - Characterize residual from backflow measurements & models
  - Weighted temporal integration to determine net-charge characteristics
- Apply at Cummins to characterize cylinder-charge dynamics
  - Spatial & temporal backflow mapping
  - Assess design tools
  - Assess advanced control strategies for viability & efficiency gains
- Accelerate development of low-cost Clean, Fuel-Efficient & Durable engines

Technical Progress: *Summary*


4 Parallel EGR Probes

- **Background: Laser-based Multiplex EGR Probe**
  - 4 simultaneous probes – faster & more extensive mapping
  - Improved sensitivity, linearity and temporal resolution
- **Characterizing Charge Components & Fluctuations**
  - Directly measure residual backflow & external EGR
  - Measurements & models to identify cylinder-residual nature
  - Assessing cylinder charge & advanced control strategies
- **Developing Multi-Color Multi-Species EGR Probe**
  - Measures CO_2, H_2O & Temperature of cylinder-charge components
  - Quantifies both hot (backflow) and cool (external EGR) species
  - Improved characterization of cylinder charge
- **New EGR Probe Tip for End-On-Flow Orientations**
  - Enables measurements down intake runner behind intake valve
- **Applications planned for CRADA & SuperTruck projects**
  - July (SuperTruck) & October (CRADA)

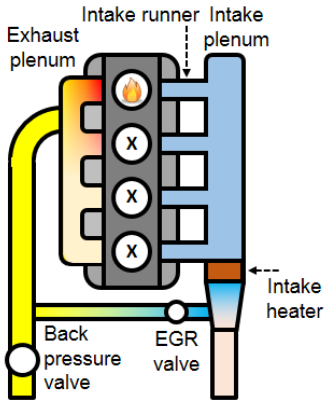
Technical Progress: Backflow Proof-of-Principle Measurements

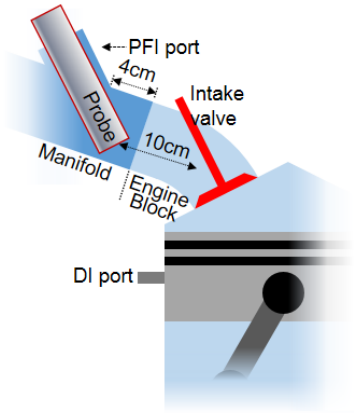


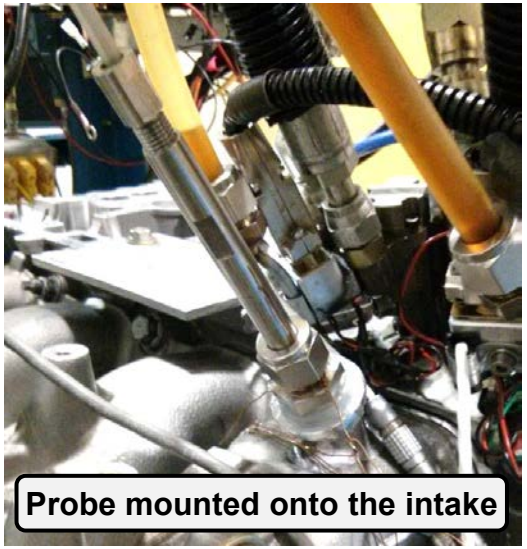
- **Single-cylinder Research Engine**
  - Modified 2.0L gasoline Ecotec engine
  - Three cylinders disabled
  - Laboratory air handling system
- **Fully variable valve actuation**
  - Enables broad residual-backflow variations
  - Excellent demonstration capability

Single-cylinder engine geometry specs

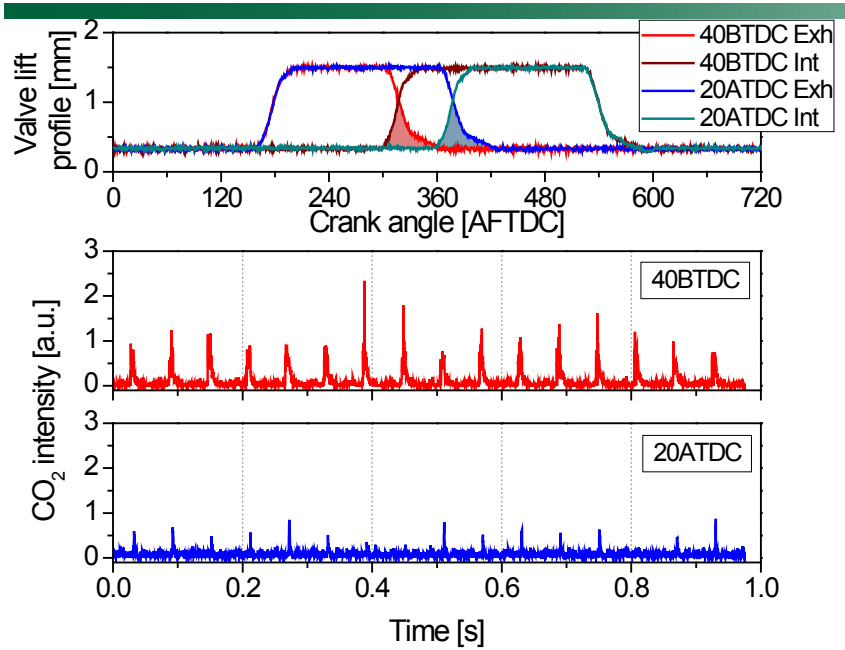
Bore (mm)	86.0
Stroke (mm)	86.0
Compression ratio	11.85
Fuel injection system	Direct injection, side-mounted

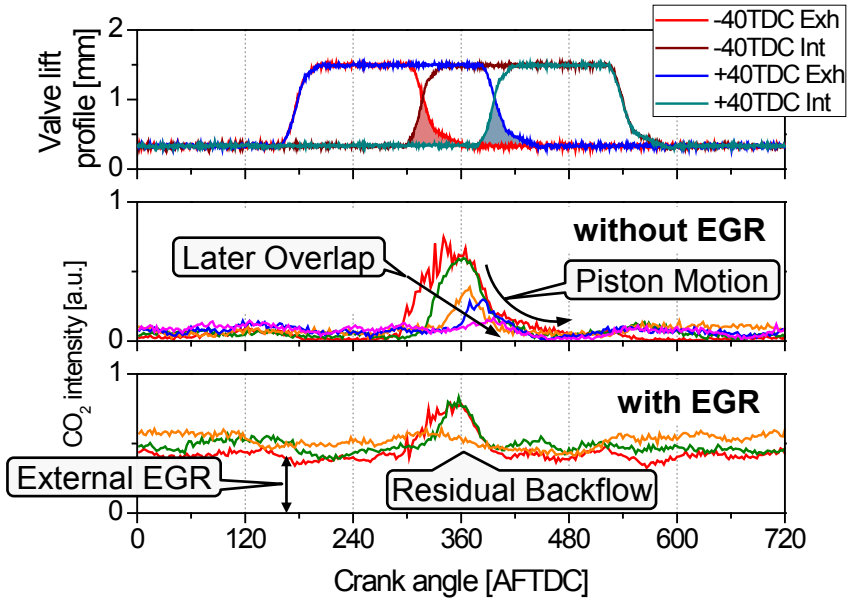






Technical Progress: Backflow & EGR Fluctuations Measured





Valve overlap-timing sweep

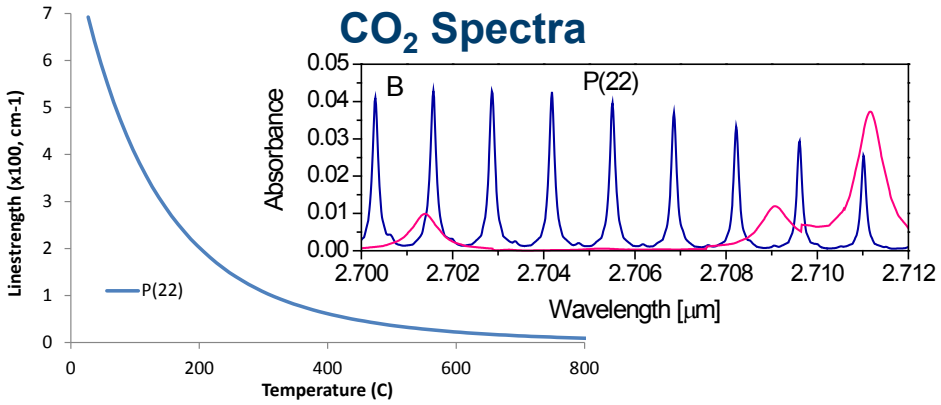
- Backflow varies with overlap timing
  - Piston moving up at 40BTDC
  - Piston moving down at 20BTDC
- Cycle-specific backflow events
  - Varies from cycle to cycle
  - Different CO_2 pulse levels

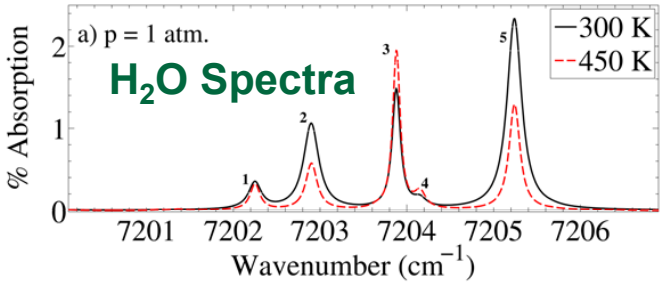
Residual Backflow vs. External EGR

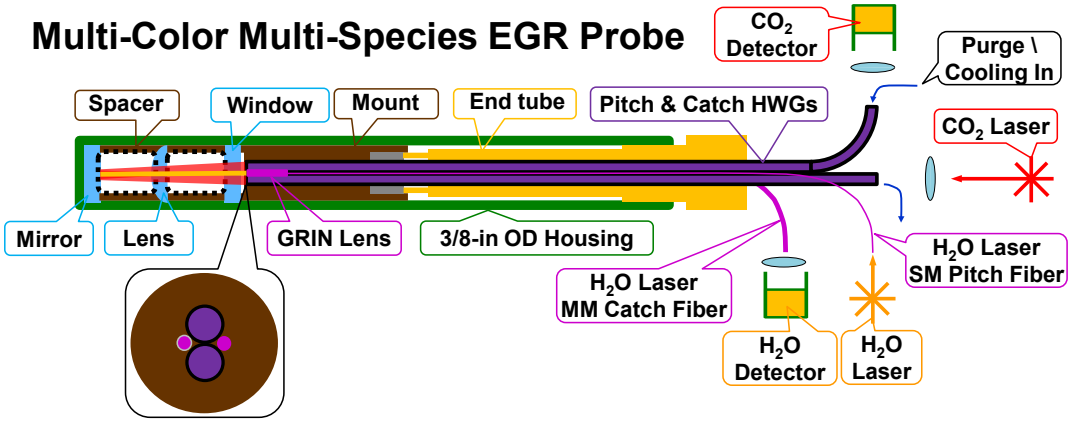
- EGR creates CO_2 baseline
- Backflow creates CO_2 pulse
- Relate backflow to cylinder residual
  - *Via heat-transfer & other models*
- Integrate Backflow & External EGR
  - Weight by crank-angle displacement

Backflow and External EGR Timing & Magnitude Measured

Technical Progress: Develop Multi-Color Multi-Species EGR Probe





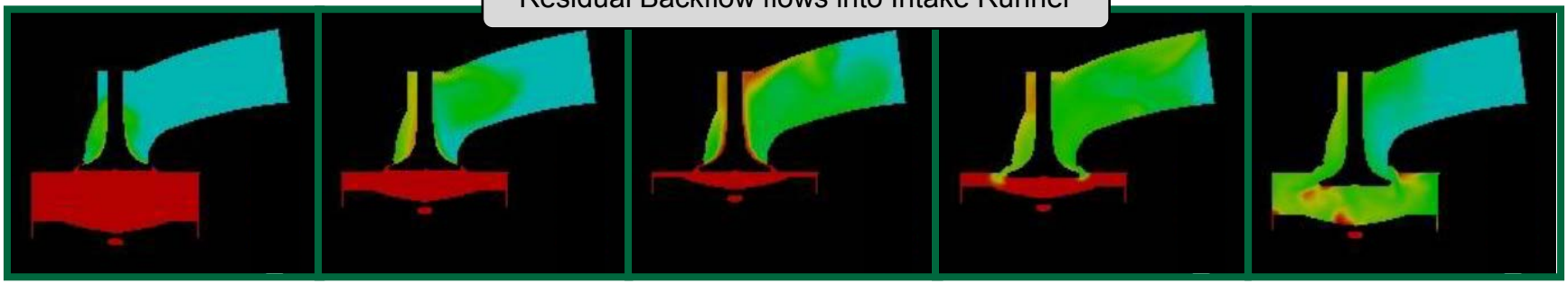


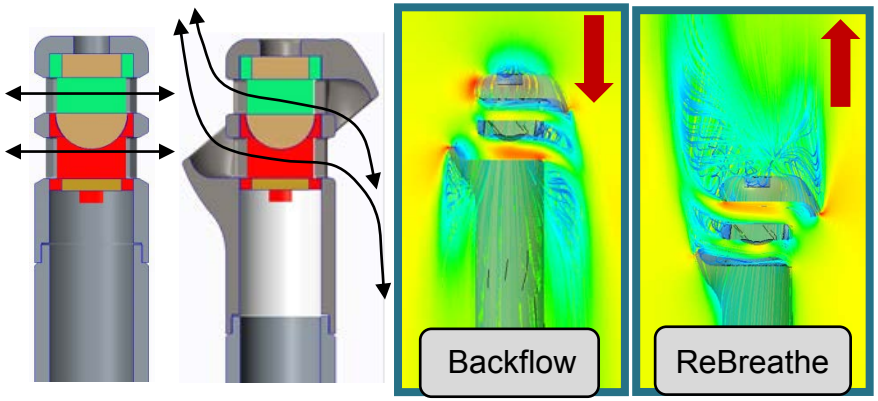
Diagnostic Advances Required

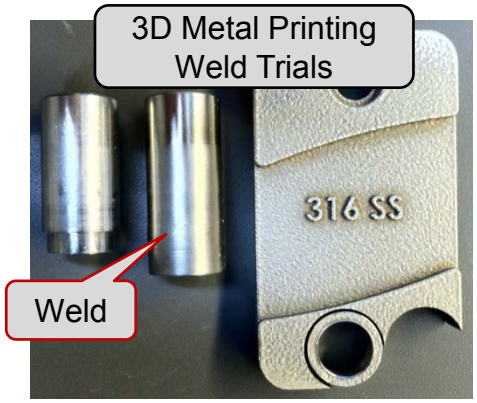
- CO_2 via single P(22) line
  - Absorption ∝ [CO_2] & Temp.
  - External EGR: Cool CO_2
  - Will underestimate Hot CO_2
- Need temperature correction
  - Backflow will be hot
- Add H_2O diagnostic
  - 2nd laser scans over 5 lines
  - Lines varying Temp sensitivity
  - Determine [H_2O] & Temp
  - Use T to correct [CO_2]
- Fast CO_2, H_2O & T diagnostic
  - Redundant EGR measures
- Probe modifications required
- July campaign scheduled

EGR Probe Improvements Enable Cylinder-Charge Characterization

Technical Progress: Develop End-on-Flow EGR Probe Tip







EGR Probe Improvements Required

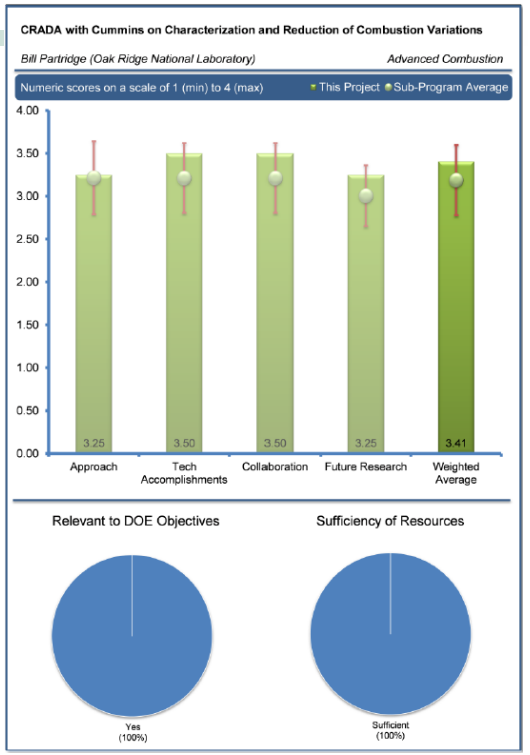
- EGR Probe designed for cross flow
- Backflow will be end-on flow
  - Probe access is down intake runner
- Modified tip designed
  - Gas cross-flows through probe ducts
- 3D 316SS Metal Printing
  - Enables complex geometry
  - Excellent weld-trial results
- Replaces standard EGR Probe tip
- *Led by SuperTruck Partnership*

Modified Probe Enables Backflow & External EGR Measurement

Responses to 2013 Review Comments

Numerous Positive Comments:

- "very unique and systematic approach"
- "good approach supporting work to achieve SuperTruck's 55% BTE target"
- "making very good progress"
- "making these measurements in real engine situations is a major accomplishment"
- "very strong collaborative relationship with Cummins"
- "project is very well-defined and planned"
- "This project makes fuel-economy advances via engine-intake improvements a refined engineering possibility"
- "project work supports overall DOE objective on developing advanced fuel efficient engines"



Recommendation:

- "apparently not making this technology available to the other participants in the SuperTruck program"
- "would like to see this project technology be rolled out to other HD engine manufactures"
  - ***All of the CRADA-developed technologies are available to any organization***
    - ***These include the EGR Probe, SpaciMS, Fuel-in-Oil***
    - ***The CRADA has always shared the diagnostics while keeping certain applications protected***
    - ***Each of these diagnostics has been applied outside the CRADA via funds-in projects***
    - ***The ORNL team is very interested in working with any interested customer***
  - ***This broad availability was specifically mentioned in the 2013AMR presentation***
  - ***Moreover, we have presented EGR Probe applications to the Advanced Combustion and Emission Control (ACEC) Tech Team (1-10-2013), where we communicated the availability of this and other CRADA-developed diagnostics to participating OEMs***
  - ***We will take additional measures to make this broad availability more clear***

Collaborations & Coordination with Other Institutions

- **Cummins**
  - CRADA Partner, Sam Geckler (Co-PI)
- **Cummins SuperTruck Program (ACE057, Friday 11-11:30am)**
  - David Koeberlein (PI), Rick Booth
  - ORNL is subcontractor on Cummins' VT SuperTruck project
  - ***Multi-Color EGR Probe scheduled for SuperTruck July 2014***
  - Cooperative development of Multi-Color Multi-Species EGR Probe
    - End-on-flow tip
    - Harmonic analysis & stiffening of long EGR Probes
  - Coordination of common development interests
  - Use of CRADA-developed technologies
- **University of Central Florida**
  - Professor Subith S. Vasu & Students
    - Informal collaboration outside VT Program
    - Combined CO-CO_2 probe *(see Thurmond presentation)*
    - Students at ORNL Aug. & Nov. 2013; June-Aug. 2014
- **Publications, Presentations and Patents**
  - **2013 R&D100 Award:** Fuel-in-Oil technology
  - **2 Patents:** re. oil dilution & particulate sensing
  - 1 Invention Disclosure: re. Multi-Color EGR Probe
  - **6 oral presentations** (3 invited)

R&D 100 2013 Award

Remaining Challenges & Barriers, and Proposed Future Work

Remaining Challenges:	Future Work:
• EGR Probe hardware modifications – Incorporating optics for H_2O spectroscopy – Avoiding resonance with engine harmonics	• Modify probe to incorporate H_2O & T optics • Stiffen Long EGR Probe to avoid vibration – *In collaboration with SuperTruck team*
• Instrument modifications for Multi-Color Multi-Species EGR Probe measurements	• Modify instrument to incorporate H_2O & Temp. – Hardware: laser, multiplex unit, detection – Software: control, data acquisition & analysis • CO_2 temperature-compensation methods
• Modify instrument for closed-loop control studies	• Determine analysis speed & accuracy tradeoffs – Real-time analysis for control assessment – Slower post-analysis for improved accuracy – Requirements & tradeoffs to be defined by team
• Applications for advancing engine efficiency – EGR & charge uniformity, combustion uniformity – Tuning and validating design models – Two campaigns at Cummins Technical Center	• Assess nature of cylinder-charge components – Spatial, cyl-to-cyl. & cyc.-to-cyc. uniformity – Calibrate simple scavenging model in GTPower – Campaigns in July (SuperTruck) & Oct. (CRADA)
• Determining net cylinder charge from component measurements	• Apply campaign insights to initial development • Further development – Models linking backflow to cylinder-residual nature – Weight factors for backflow & intake charge – Temporal (crank angle) integration methods

Summary

- **Relevance**
  - CRADA work enables improved cylinder-to-cylinder & cycle-to-cycle combustion uniformity
  - This in turn enables DOE goals for improved fuel efficiency and durability
- **Approach**
  - Develop diagnostic to measure spatial & temporal uniformity of cylinder-charge components
  - Apply diagnostic to advance engine technology
    - Assess specific hardware architectures
    - Tune, validate & improve design simulation tools (models)
    - Assess closed-loop control strategies & associated efficiency gains
- **Technical Accomplishments**
  - Residual-backflow and external EGR measurements demonstrated
  - Advanced EGR Probe designed & specified for quantifying backflow & external EGR
  - End-on-flow EGR Probe tip designed *(in collaboration with SuperTruck project)*
- **Collaborations**
  - Application of EGR Probe to Cummins' SuperTruck 55% BTE Goals
  - EGR Probe design & development work outside VT program with U. Central Florida
  - R&D100 Award, numerous presentations and two patents
  - EGR Probe available to users outside the CRADA
- **Future Work**
  - Modify EGR Probe for quantifying backflow and external-EGR charge components
  - Apply modified probe in CRADA & SuperTruck campaigns to characterize charge uniformity
    - Assess hardware, design models and advanced closed-loop control strategies
  - Develop methods for determining net charge nature from backflow & EGR measurements