



Co-Optimization of  
Fuels & Engines

# Exploratory Advanced Compression Ignition Combustion Tasks

John Dec, presenter

## Team PIs:

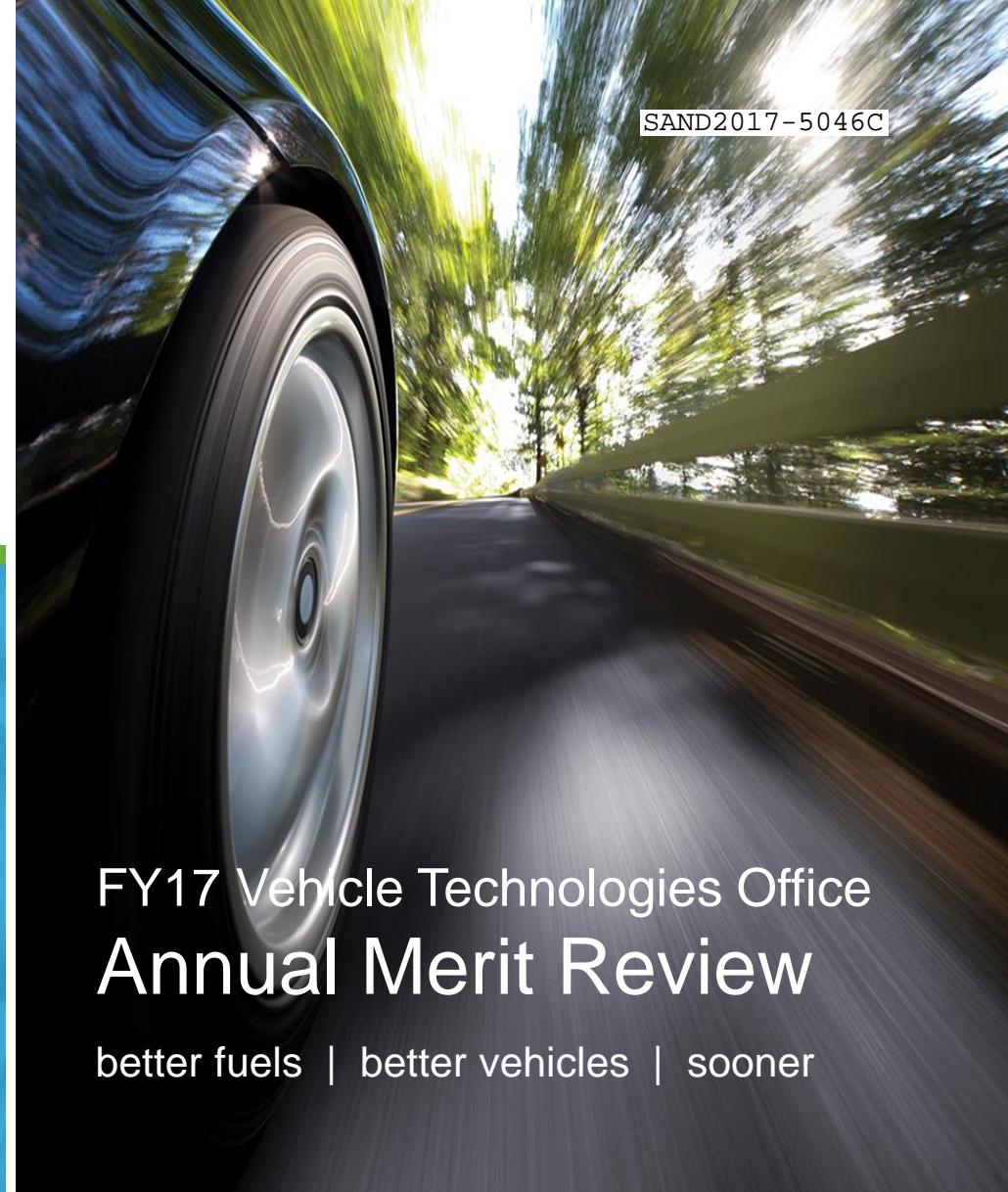
Steven Ciatti, ANL    Andrew Ickes, ANL  
Scott Curran, ORNL    Chuck Mueller, SNL  
John Dec, SNL    Mark Musculus, SNL

June 8, 2017

Project ID: FT056



Energy Efficiency &  
Renewable Energy



SAND2017-5046C

## FY17 Vehicle Technologies Office Annual Merit Review

better fuels | better vehicles | sooner

VTO Program Managers: Gurpreet Singh,  
Kevin Stork, Leo Breton & Michael Weismiller

# Overview



## Timeline

- Project start date: 10/1/2015
- Project end date: \* 9/30/2018
- Percent complete = 56%

## Budget

Total budget for all Advanced Compression Ignition Tasks

- FY16 = \$1663
- FY17 = \$1903

## Barriers / Research Needs

- Insufficient understanding of fuel effects on Advanced Compression Ignition (ACI) Combustion
- Need for improved understanding of low-temperature ACI fundamentals
- Rapid control of combustion timing in low-temperature ACI engines
- Advanced fuel-injection strategies

## Partners

(in order of Co-Optima tasks)

- ANL, Ciatti/Kolodziej – GCI (Gasoline CI)
- SNL, Dec – LTGC (Low-T Gasoline Comb.)
- ORNL, Curran – RCCI, metal engine
- SNL, Musculus – RCCI, optical engine
- SNL, Mueller – Advanced Diesel, LLFC
- ANL, Ickes – Merit Function for ACI

\* Start and end dates refer to three-year life cycle of DOE lab-call projects. Co-Optima is expected to extend past the end of FY18.

# Overview: Exploratory Advanced Compression Ignition (ACI) Combustion Tasks



**Projects focus on ACI Strategies using both gasoline-like and diesel-like fuels (previously Thrust II)**

- **Investigate “boosted-SI” fuel compatibility with ACI Gasoline strategies**
  - E2.1.1 Gasoline Compression Ignition (GCI), ANL Ciatti/Kolodziej ⇒ \$175k
  - E2.1.2 Low Temperature Gasoline Combustion (LTGC), SNL Dec ⇒ \$175k  
Premixed and Partially Stratified
- **Accelerate ACI combustion-system development for Diesel-like and Dual-Fuel strategies**
  - E2.2.1 Accelerate development of ACI ⇒ FY17 focus on Reactivity-Controlled Compression Ignition (RCCI): Multi-cylinder engine, ORNL Curran ⇒ \$350k
  - E2.2.2 Fuel effects on RCCI: Optical engine, SNL Musculus ⇒ \$175k
  - E2.2.3 Mixing-Controlled CI Combustion & Fuels Research, SNL Mueller ⇒ \$788k
- **Merit Function development for ACI engines & Technical Roll-up**
  - E2.3 ANL/ NREL/ ORNL/ SNL – Led by ANL Ickes ⇒ \$240k

# Co-Optima Milestones: Exploratory ACI Combustion Tasks



## Tracked Co-Optima Milestones

Milestone	Date
<b>Accelerate ACI Combustion System Development for Dual-Fuels</b>	
<b>ORNL:</b> Complete coordinated experiments with SNL with selected fuel combinations for high- and low-delta dual-fuel ACI;	6/30/2017
<b>SNL:</b> Use fuel-tracer/combustion-intermediate fluorescence to quantify coupling of fuel properties with physical processes.	9/30/2017
<b>Merit Function for ACI Engines &amp; Technical Roll-up</b>	
<b>ANL:</b> Draft initial merit function for 1-2 key fuel properties for Thrust II combustion concepts.	9/30/2017

- Work is on track to meet scheduled milestones

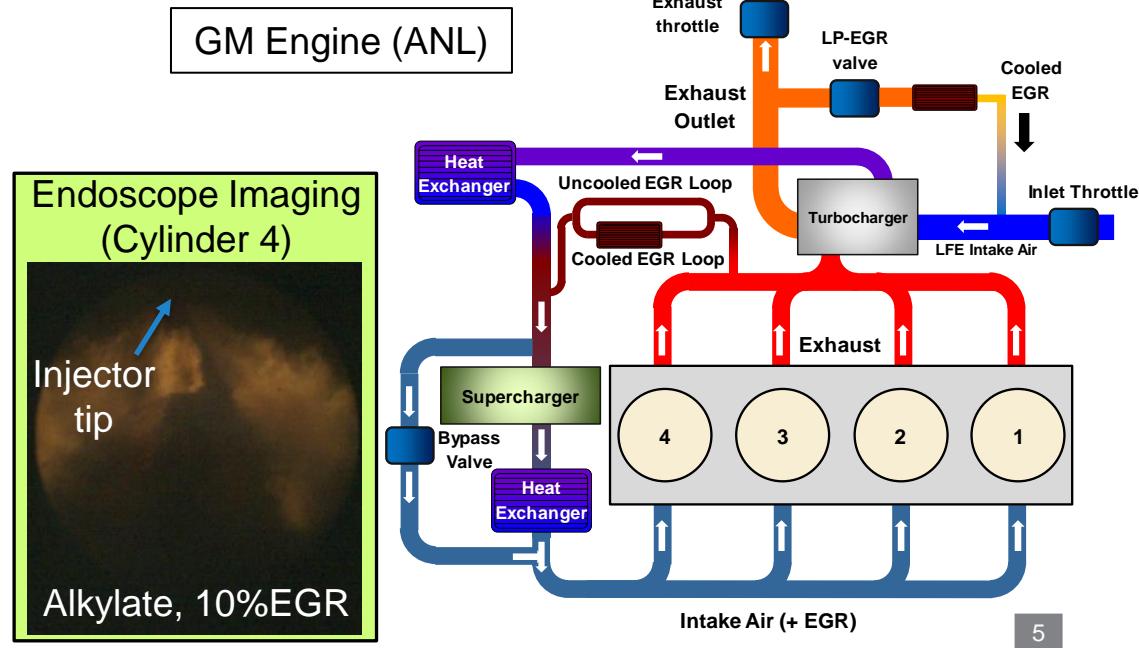
# ANL (Ciatti) \$175k: Gasoline Compression Ignition of “Boosted-SI” Fuels: Objective and Approach



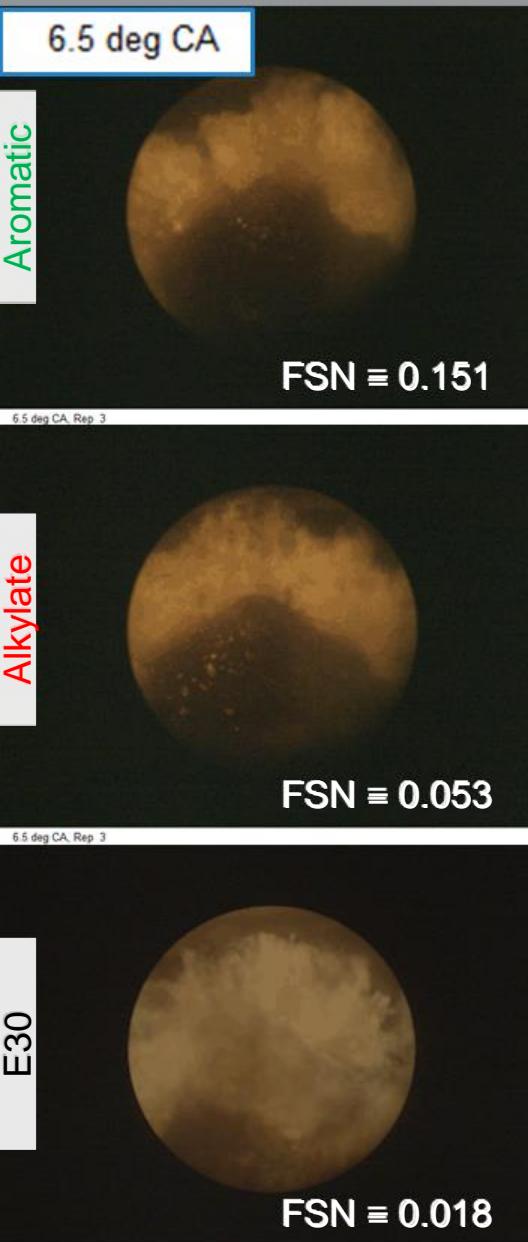
- **Objective:**
  - Demonstrate **Gasoline Compression Ignition (GCI)** combustion with high-octane (**Boosted-SI**) fuels in a 1.9L GM engine.
  - Investigate parameters that affect engine performance and emission; and identify condition with desirable outputs (i.e. **emission, noise, efficiency**)
- **Approach:** double injection strategy to control combustion phasing (**CA50 ~ 5 aTDC**) while maintaining combustion stability ( $\text{COV}_{\text{IMEP}} < 3\%$ ) and noise ( $< 90 \text{ dB}$ ), low FSN ( $< 0.1$ ). Parametric study of:
  - **Exhaust Gas Recirculation**
  - **Global Lambda**

Impact on

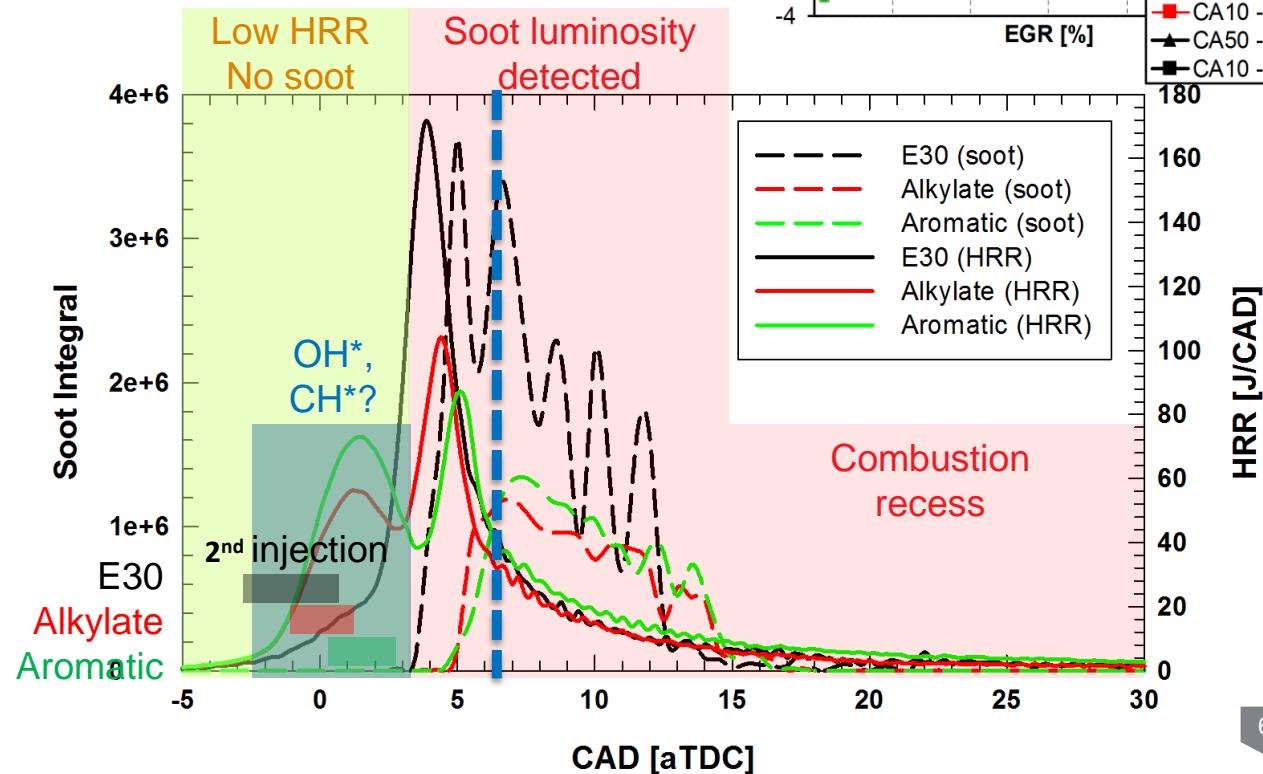
Parameter	Value
Engine 1.9L GM 4-cylinder (17.8:1 CR)	
Engine Speed [rpm]	1000
Engine Load [bar BMEP]	3-6
Fuel – 98 RON: Aromatic, Alkylate, E30	
Injection Pressure [bar]	600
Start of Injection [°aTDC]	-50/varied
Fuel Split (~ % by duration)	55/45
EGR [%]	20 (0-30)
Boost Pressure [bar(a)]	1.4 (1.0-1.7)
Intake Air Temp [°C]	55 (35-85)
Global $\lambda$ (= 1/ $\Phi$ )	1.8 (1.6, 2.0)



# ANL (Ciatti) : Gasoline Compression Ignition of “Boosted-SI” Fuels: Accomplishment and Results



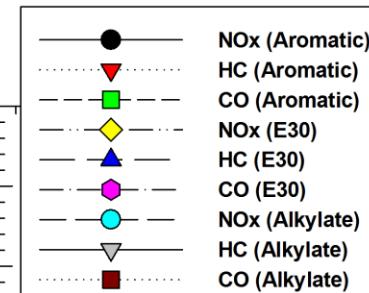
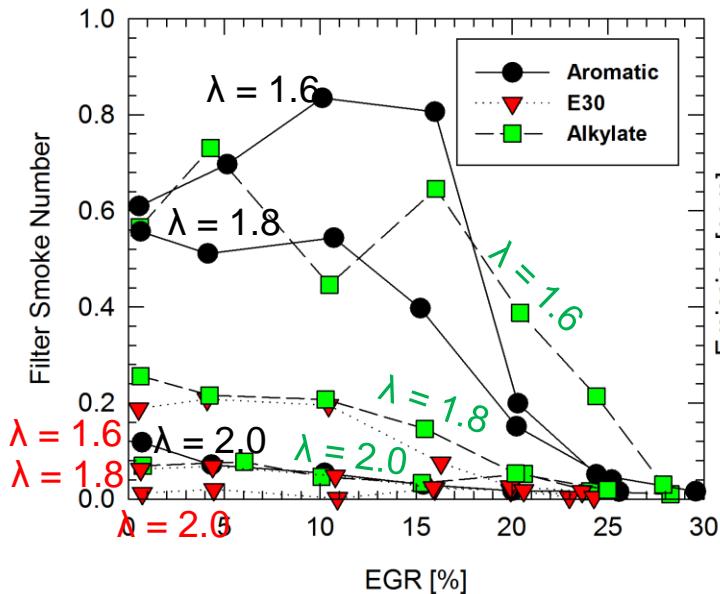
- Delayed CA10 with increasing EGR (CA50 stay constant)
- Endoscope images for low FSN condition (20% EGR cases are shown)
- Soot luminosity only seen at high HRR. Aromatic/Alkylate produce more engine-out soot than E30
- E30 forms and oxidizes soot quickly



# ANL (Ciatti): Gasoline Compression Ignition of “Boosted-SI” Fuels: Results (cont'd) and Future Plans



## Global Lambda and EGR Sweep

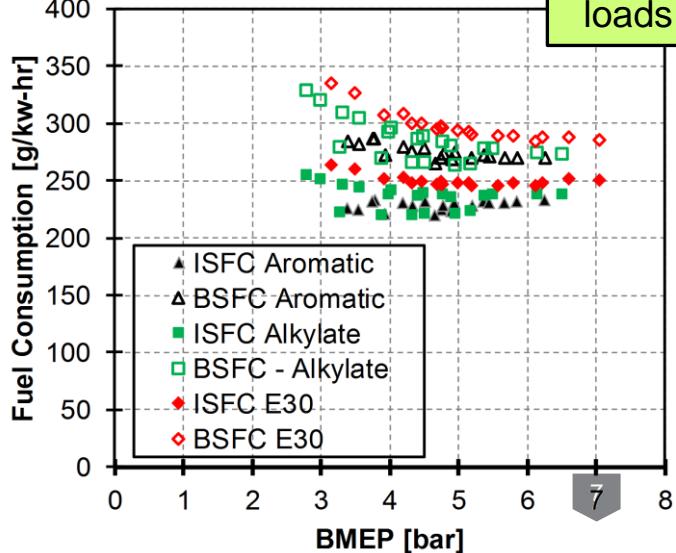


## Emission vs. EGR (Lambda = 1.8)

- Highest FSN in Aromatic
- Above 25% EGR (LTC condition), FSN is reduced significantly
- Relatively low NOx/HC/CO

## ISFC & BSFC at Various Loads

Most tested loads



## Future work:

*Any proposed future work is subject to change based on funding levels*

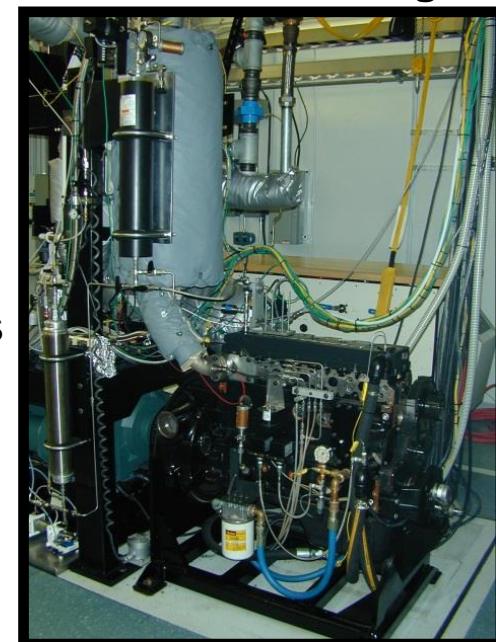
- Improve engine efficiency and BSFC with turbocharger operation and injection strategy (higher BMEP points)
- Endoscope imaging for OH\* chemiluminescence in low HRR region where soot is absent
- PM measurement for GCI soot characteristics

# SNL (Dec) \$175k: “Boosted-SI” Fuel Compatibility with Low-Temperature Gasoline Combustion (LTGC)



- **Relevance:** LTGC provides efficiencies at or above those of diesel engines.
  - Substantial reduction in fuel consumption vs. SI  $\Rightarrow$  use light-distillates efficiently for more effective use of crude oil supplies.
  - Ultra-low NOx and PM minimize aftertreatment and cost
- **Project Objective:** Determine / develop optimal LTGC fuel
  - **FY17 Objectives:** Investigate the performance of “boosted-SI” fuels for LTGC and the validity of the Central Fuel Hypothesis. Are RON & MON sufficient metrics for LTGC?  
 $\Rightarrow$  Also provide well-characterized data for kinetic model development.
- **Approach:** Use Sandia single-cylinder LTGC engine
  - Well-controlled experiments for Premixed, G-DI, & PFS fueling
  - Work w/ FP team & Boosted-SI engine researchers to develop fuel test matrix  $\Rightarrow$  Added two additional fuels to matrix.
- **Collaborations:**
  - ORNL: Development of fuel test matrix for boosted SI engines
  - LLNL: Apply modeling to search for alternative fuels with:  
both 1) high RON & octane-sensitivity & 2) good  $\phi$ -sensitivity
  - GM: Regular meetings; discuss FP effects, e.g. OI & K-factor
  - USCAR: Advanced Combustion & Emissions Control LTC Fuels Survey Team

**LTGC Research Engine**

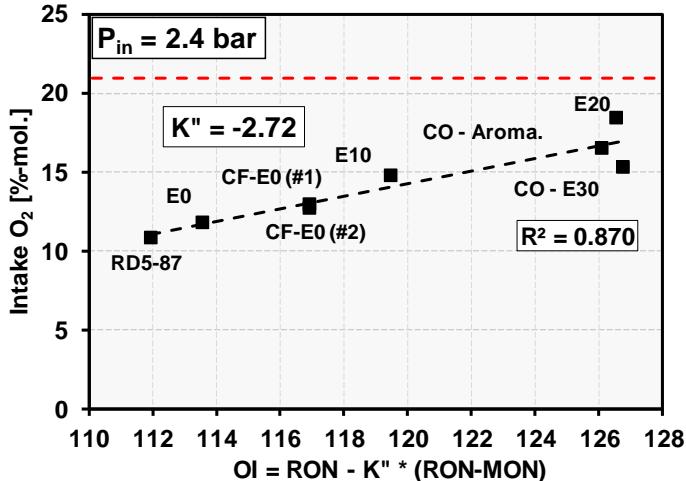


# SNL (Dec): “Boosted-SI” Fuel Compatibility with Low-Temperature Gasoline Combustion (LTGC)

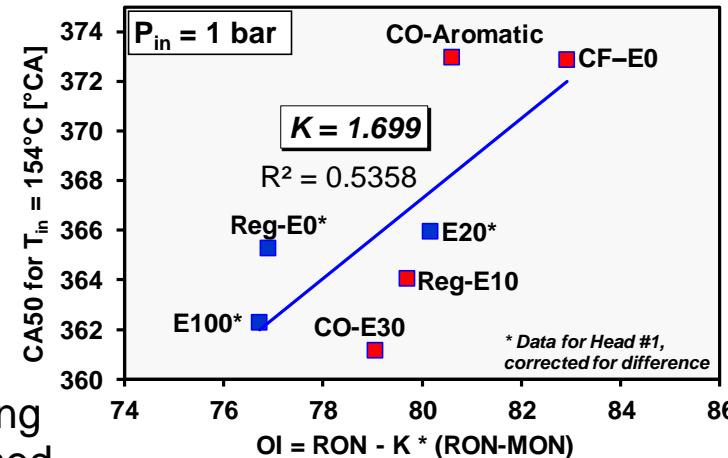
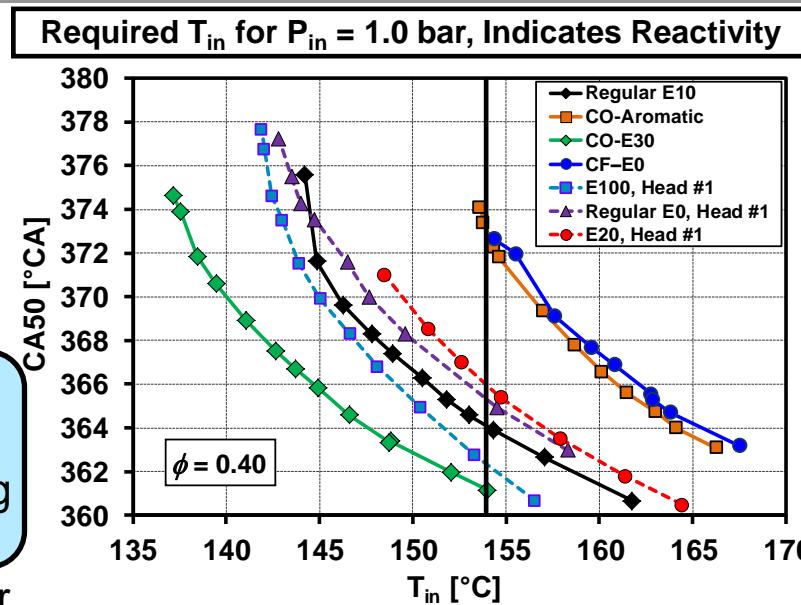


## Accomplishments – Fuel Reactivity

- Designed fuel test matrix with 5 fuels, all RON = 98, Sensitivity =  $\sim 10.5$
- $P_{in} = 1.0$  bar: Surprisingly, E30 is most reactive fuel tested, & high-aromatic is nearly lowest.
  - Octane Index (OI) gives very poor correlation for these fuels for LTGC at  $P_{in} = 1$  bar.  $R^2 = 0.536$
  - RON and MON appear not sufficient for specifying fuel reactivity for lean LTGC ( $\phi = 0.4$ ) at this cond.
  - Perhaps this is because E30 is less  $\phi$ -sensitive, or differences in HOV  $\Rightarrow$  Further studies are planned.
- $P_{in} = 2.4$  bar: Use OI based on Intake  $O_2$ , since  $T_{in} = 60^\circ C$  for all.



- This OI correlates fuels fairly well at  $P_{in} = 2.4$  bar,  $R^2 = 0.870$ .
- Further understanding of this intake- $O_2$  based OI is needed.



# SNL (Dec): “Boosted-SI” Fuel Compatibility with Low-Temperature Gasoline Combustion (LTGC)



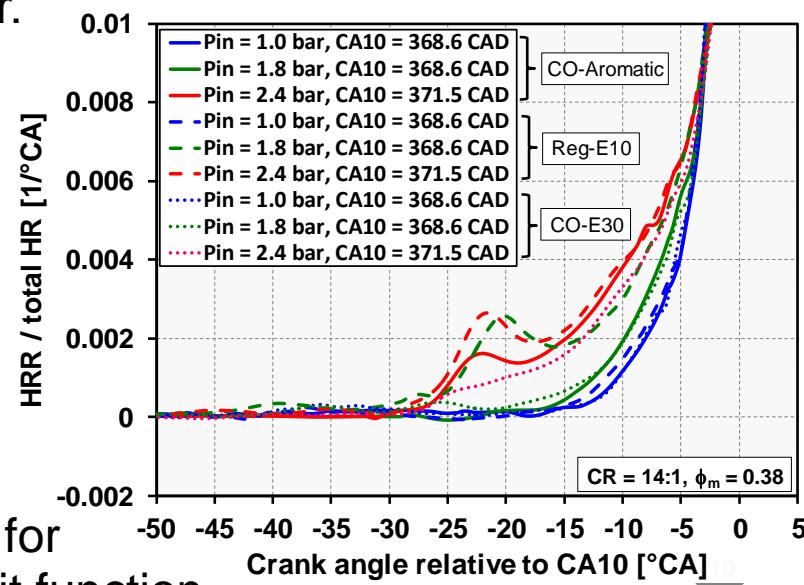
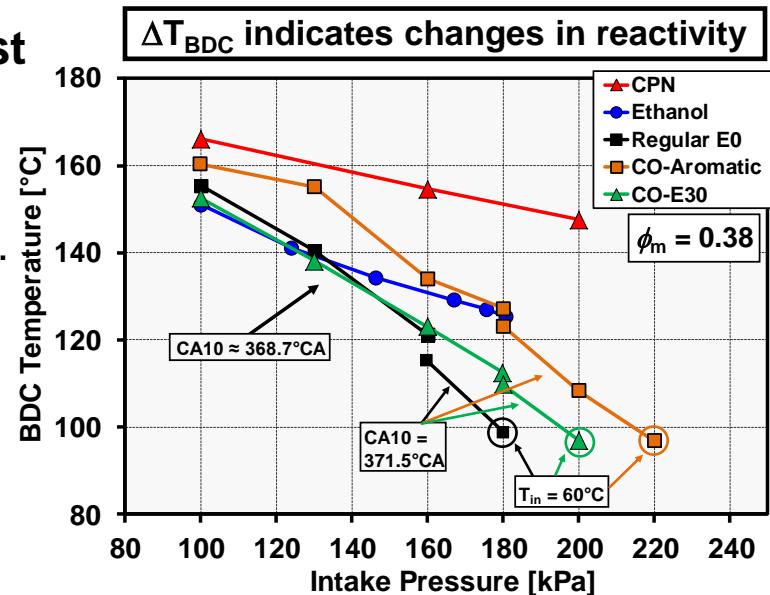
## Accomplishments: Reactivity Changes w/ Boost

- Increased fuel autoignition reactivity with boost is a key challenge for both LTGC and SI.
  - LTGC: High EGR required for CA50 control limits O<sub>2</sub>.
  - SI: Increased knock propensity limits CR.
- Despite higher RON & Sens, E30 has similar reactivity to Reg-E0 for  $P_{in} = 1.0 - 1.6$  bar.  
 $\Rightarrow$  Somewhat less reactive for higher  $P_{in}$ .
- High-aromatic fuel is significantly less reactive than Reg-E0 at all  $P_{in}$ .  $\Rightarrow$  Large diff.  $P_{in} \geq 1.8$  bar.
  - Lower ITHR for hi-aromatic & E30 at  $P_{in} = 1.8$  bar vs. Reg-E0  $\Rightarrow$  agrees with difference in reactivity
  - Also agrees with lower  $\phi$ -sensitivity (for PFS).

## Future Work:

*Any proposed future work is subject to change based on funding levels*

- Complete E30 evaluation,  $\phi$ -sens. & high loads.
- Evaluate the other three fuels in test matrix  
 $\Rightarrow$  High-Olefin, High-Cycloalkane, & Alkylate
- Investigate Co-Optima fuels with good potential for full-time LTGC-ACI engines  $\Rightarrow$  Support ACI merit function.



# E.2.2.1 ORNL (Curran) \$350k: Accelerate Development of ACI

## E.2.2.2: SNL (Musculus) \$175k: Fuel Effects on RCCI



### Motivation for Using RCCI in ACI Engines

On-the-fly in-cylinder mixing of two fuels =

#### **Control of combustion phasing & HRR**

- Global octane number adjusted by fuel ratio
- Reactivity stratification by injection timing

#### RCCI Challenges

Peak pressure rise rate (PPRR) limits high load

- E30 extends limit  $\Rightarrow$  not well understood

Incomplete combustion at lowest loads

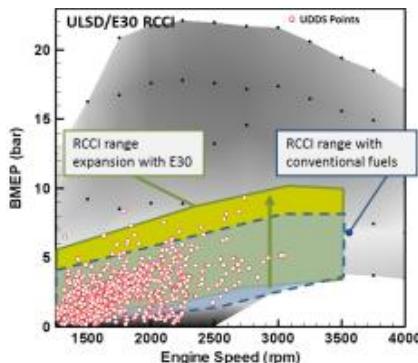
- Reasons are unclear

#### Approach for Foundational RCCI Work

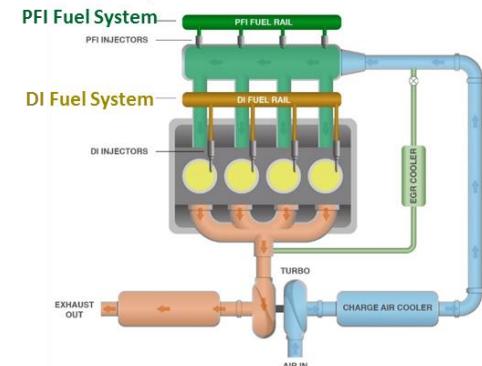
- E.2.2.1: Use ORNL multi-cylinder metal engine to identify key fuel & operating-condition combinations where an improved understanding is required.
- E.2.2.2: Use SNL single-cylinder optical engine to image in-cylinder mixing, ignition, and combustion processes at these conditions.

### **ORNL Metal Engine**

- Multi-cylinder light-duty diesel engine (PFI + DI)

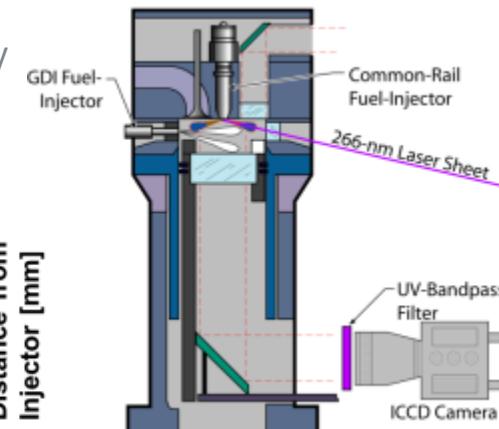
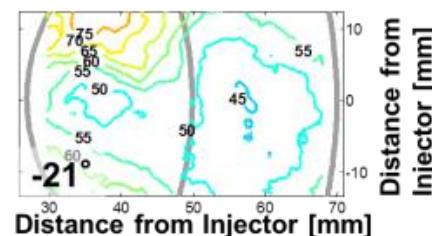


- Transient capable + emissions characterization



### **SNL Optical Engine**

- Single-cylinder heavy-duty diesel engine (GDI + DI)
- Image combustion & in-cylinder mixing (PRF)



# E.2.2.1 ORNL (Curran): Metal engine experiments to support ACI merit function & guide SNL optical work



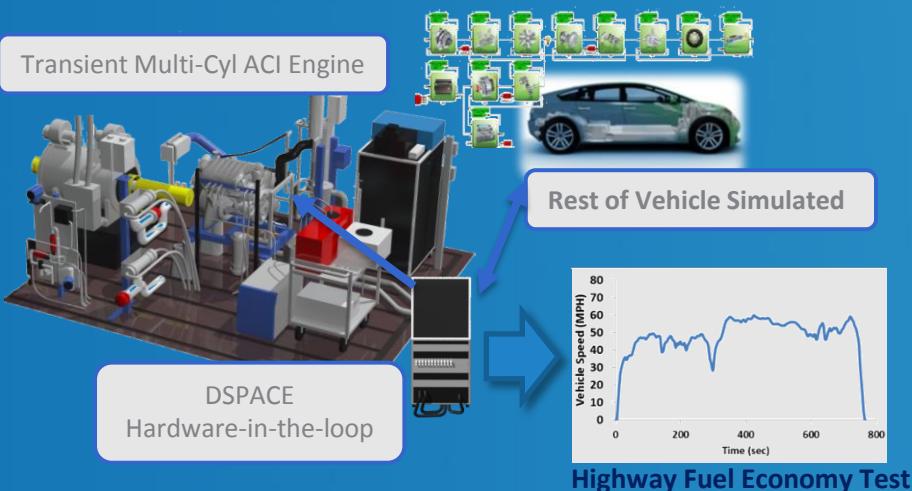
## ● E.2.2.1 Objectives

- Identify performance trends in ACI strategies spanning RCCI & GCI  
⇒ Identify desired fuel properties
- Contribute to the ACI merit function and fuel hypothesis for ACI

## ● E.2.2.1 FY 16 Results

### – FY 16 Q4 Milestone -Complete

- > Thrust 1 surrogate fuel, iso-octane, studied in steady state and transient hardware-in-the-loop experiments with diesel/RCCI multi-mode



## Current and Future Work

### – FY 17 Q3 Milestone - On Track

- > Milestone: Complete **coordinated experiments with SNL** with selected fuel combinations for dual-fuel ACI (RCCI)
  - Details on next slide + E.2.2.2
  - Included extended visit collaboration with ORNL researcher working with SNL at optical engine research facility

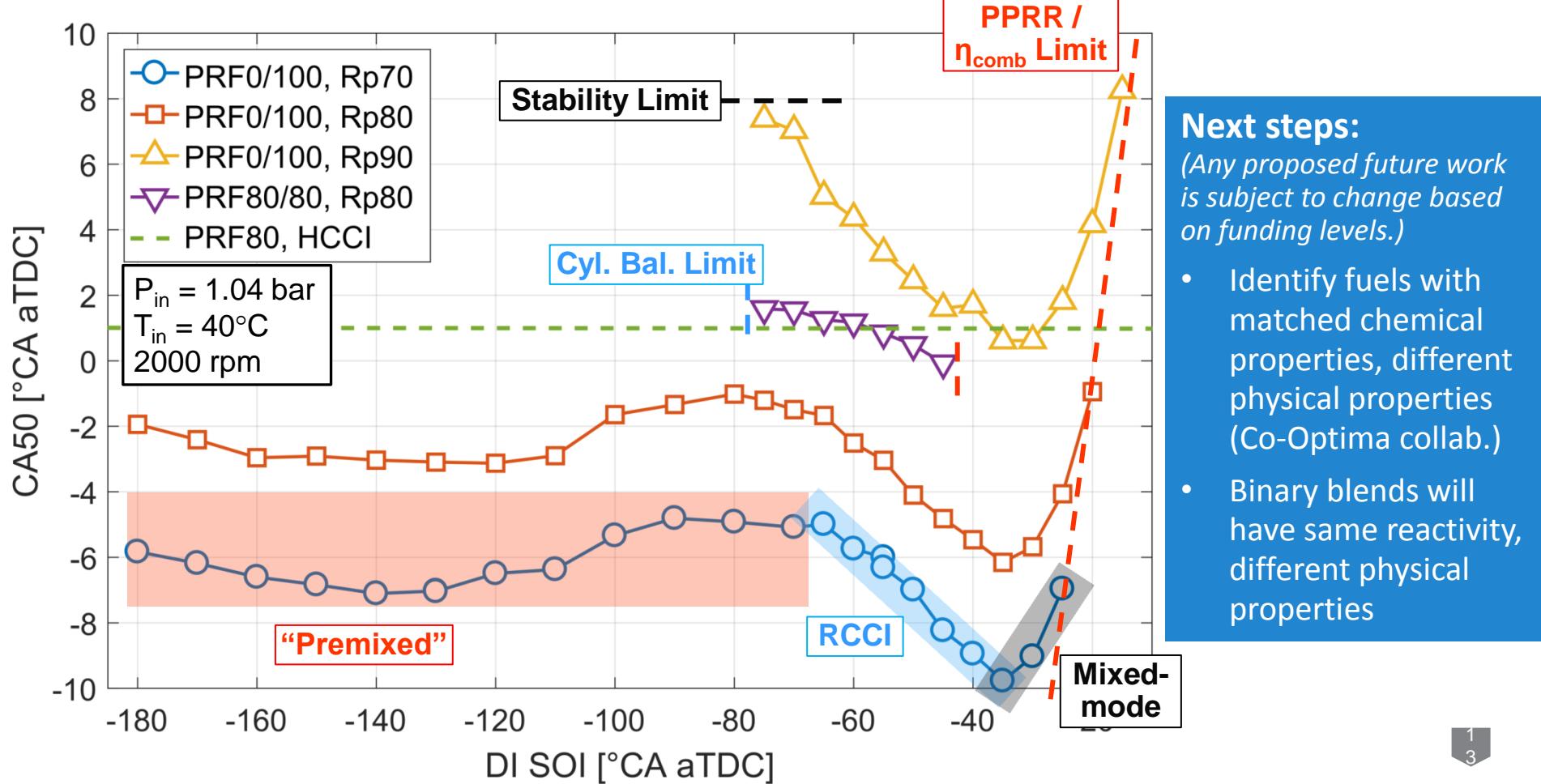
### – FY 17 Q4 Milestone - On Track

- > Milestone: Complete experimental campaign and data processing to assess fuel effects on emissions and efficiency for ACI combustion modes in **support of an ACI merit function**

## E.2.2.1 ORNL (Curran): RCCI with iso-octane and n-heptane: matched physical, different chemical properties



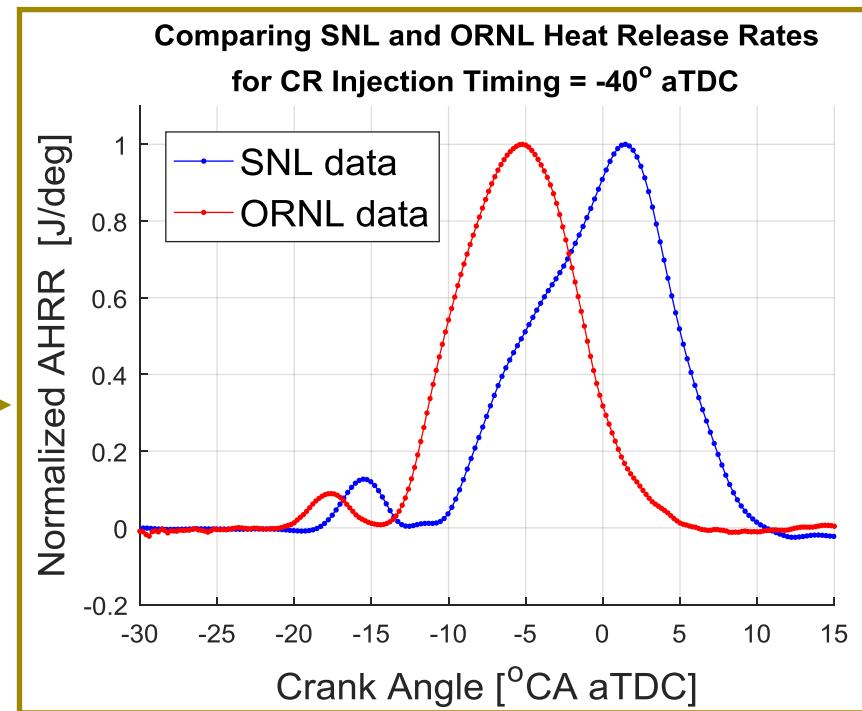
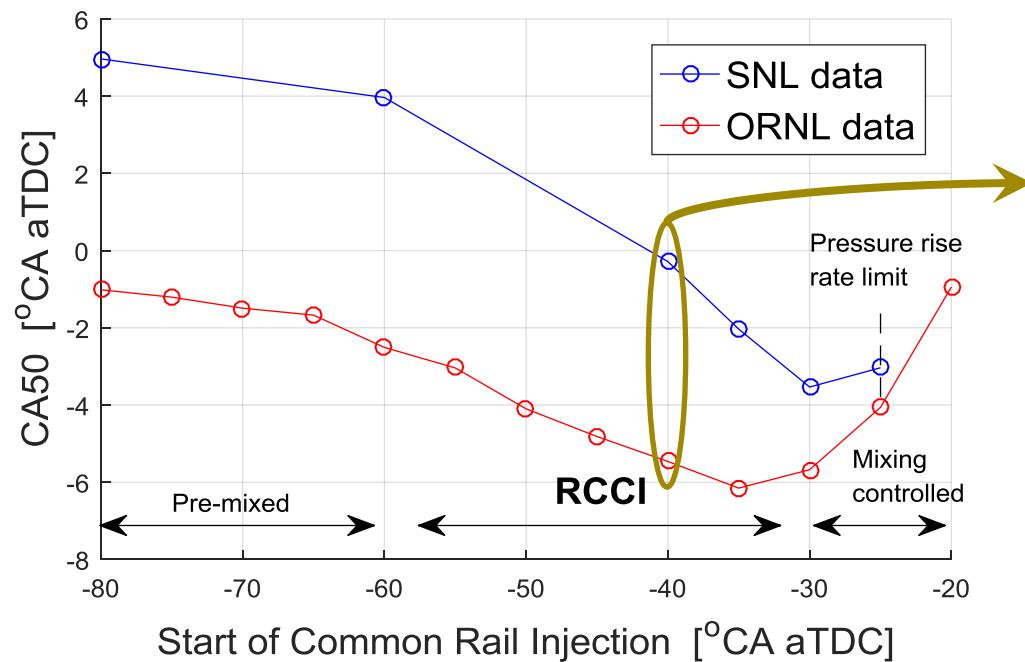
- **Results:** direct injection timing sweeps illustrate range of control authority and mode transitions
  - Binary PRF blends have same physical properties, but different reactivity
  - Maintain constant mixing and  $\Phi$  stratification while changing reactivity stratification



## E.2.2.2 SNL (Musculus): Combustion phasing dependency on common-rail injection timing matched in optical & metal engines



The mid-point of combustion heat release (CA50) depends on the injection timing of high-reactivity (PRF 0) fuel from the common rail (CR) DI injector

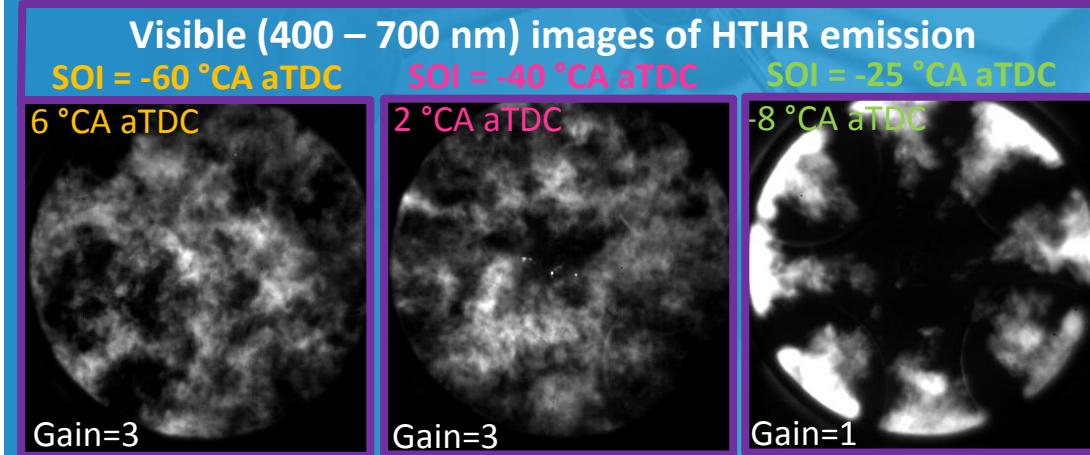
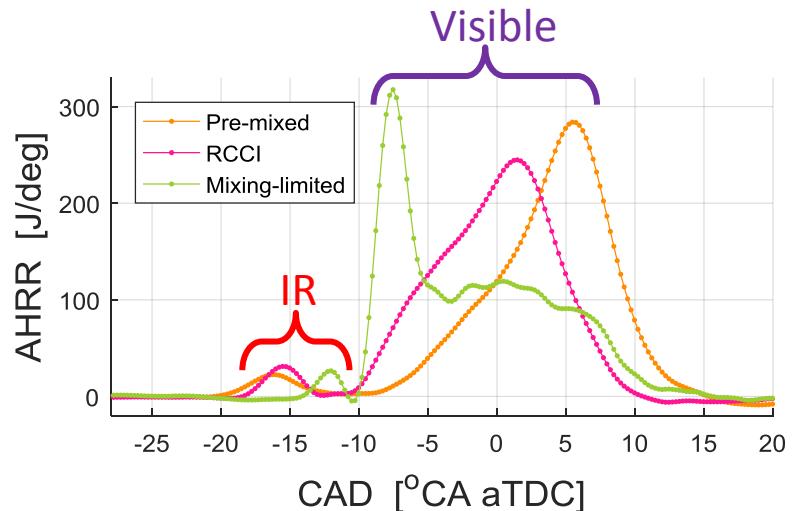
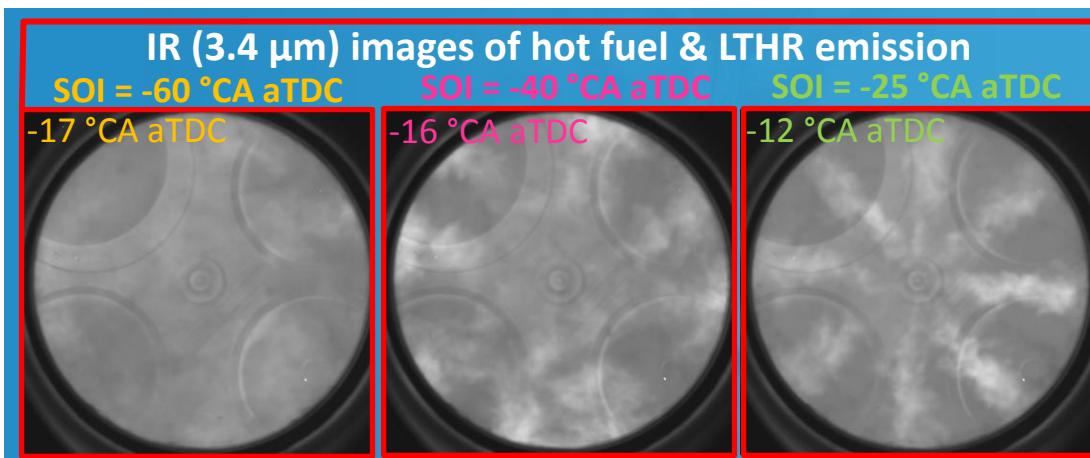
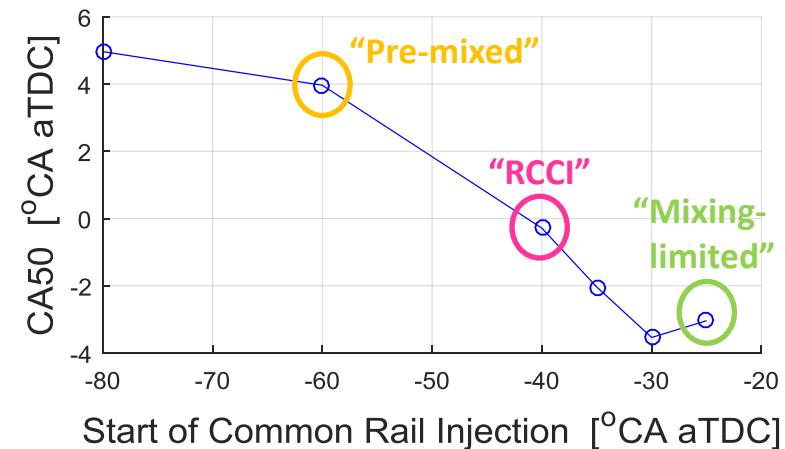


For a DI injection in the “RCCI regime,” the heat release phasing is shifted, but the curves have the same characteristic shapes

- SNL HD optical engine conditions match ORNL LD metal engine: **1. charge-gas  $\rho$  &  $T$  at DI injection, 2. premixed iso-octane fraction (80%), 3. global  $\Phi$  (0.35)**
- Even with different engine displacement (heavy-duty vs light-duty), compression ratios, and piston geometry, the **combustion characteristics are similar**, with three CA50 regimes (pre-mixed, RCCI, & mixing-controlled) and similar heat release shapes



## E.2.2.2 SNL (Musculus): Imaging diagnostics show how mixing affects ignition (IR) and combustion (visible) heat release



- Brightening jet structure in visible imaging indicates transition to richer mixtures
- Shows how mixing time affects in-cylinder distribution of combustion phenomena

### Next steps

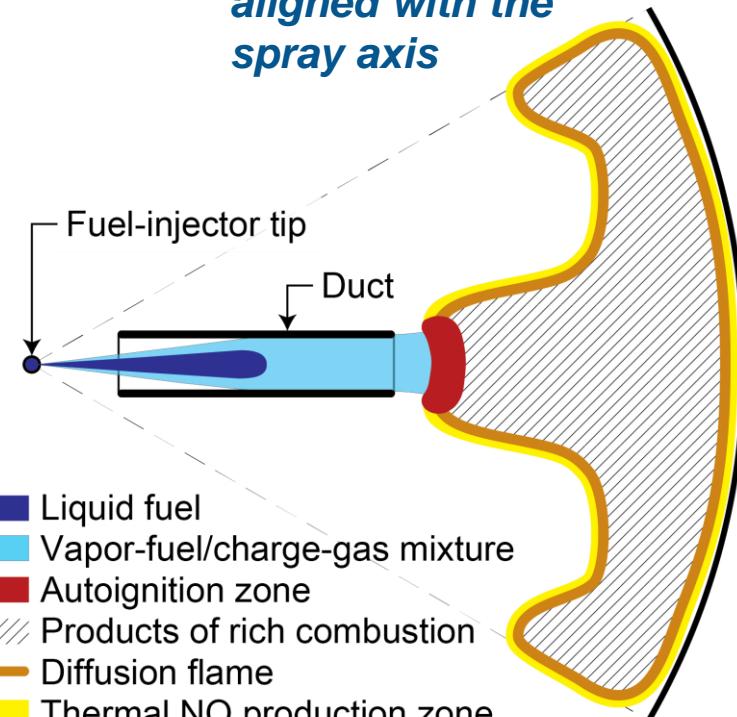
(Any proposed future work is subject to change based on funding levels)

- Follow up with laser-sheet mixing diagnostics to quantify mixing effects for these PRFs
- Image combustion phenomena for ORNL fuels with different physical properties



- **Relevance:** Mixing-controlled CI combustion is desirable for many reasons
  - > Inherently high efficiencies, low HC & CO emissions
  - > Ignition timing easily controlled by injection timing
  - > Inherently fuel-flexible (cetane # is key fuel parameter)
  - Soot is a barrier to fully achieving the above benefits
    - > Soot is a potent toxin
    - > 2<sup>nd</sup> only to CO<sub>2</sub> as a climate-forcing species
    - > Limits amount of EGR possible for NO<sub>x</sub> control
    - > Aftertreatment is expensive, has efficiency penalties (backpressure, regeneration)
- **Approach:** Use Ducted Fuel Injection (DFI) to make richest autoigniting mixtures leaner
  - **Effective at lowering soot** (see next slide)
  - Geometrically & conceptually simple
  - Tolerant to dilution for NO<sub>x</sub> control
  - Synergistic with Co-Optima oxygenated fuels, but does not require oxygenation
  - Might increase comb. efficiency by limiting over-mixing at spray periphery

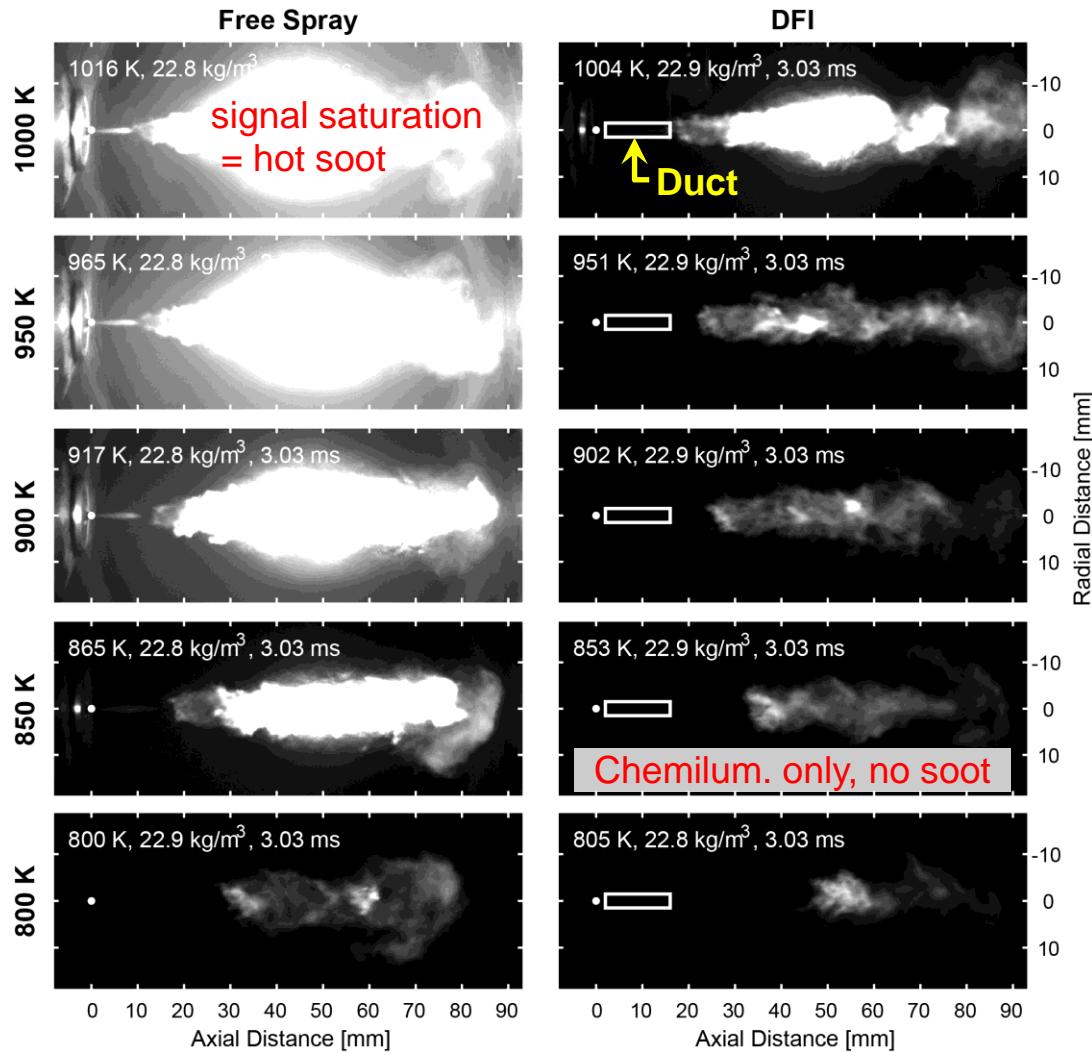
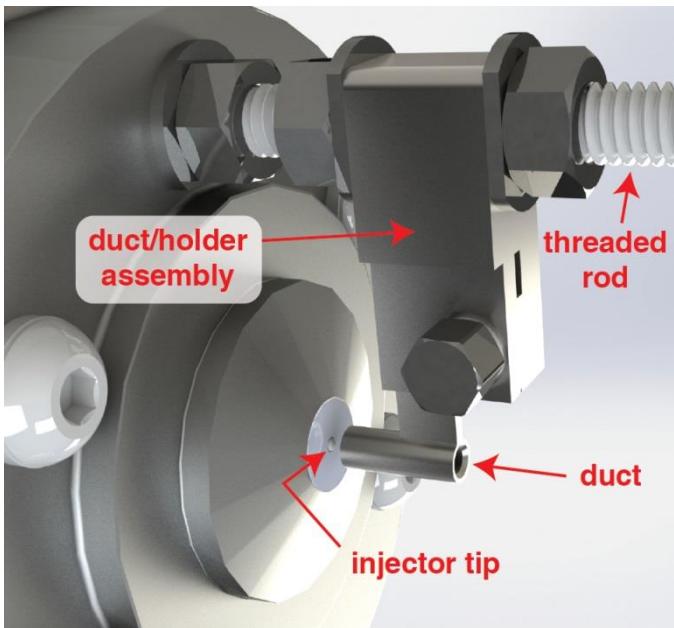
***Basic idea of DFI:***  
***Inject fuel down a small tube/duct aligned with the spray axis***



# Technical Accomplishments and Progress (1 of 2): DFI Lowers Soot over a Range of Temperatures



- DFI exp'ts were conducted in Sandia's constant-volume combustion vessel
  - 90  $\mu\text{m}$  orifice diameter
  - 1500 bar injection pressure
  - 21 mol% oxygen (no EGR)
  - n-dodecane fuel (not oxygenated)

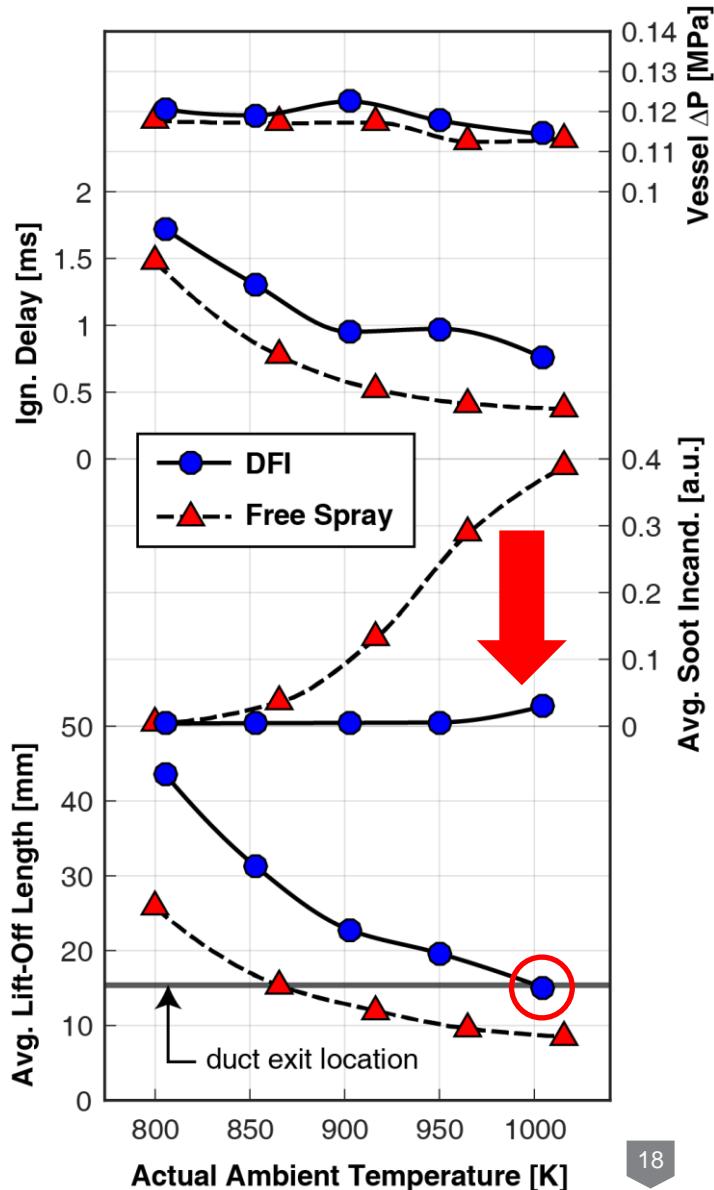


**DFI is effective at lowering or preventing soot incandescence over a range of temperatures**

# Technical Accomplishments and Progress (2 of 2): Initial Characterization of DFI Shows Promise



- Effects of DFI on combustion observables
  - Lift-off lengths increase with DFI
    - > Flame anchors to duct exit at 1000 K
  - Soot incandescence decreases by 10× or more, even when flame is anchored at duct exit
    - > Subsequent quantitative soot measurements yield similar results
  - Ignition delays increase with DFI
    - > Could increase engine noise
  - Total pressure rise ( $\Delta P$ ) in vessel is slightly, but consistently larger with DFI
    - > Suggests combustion efficiency could be higher (still investigating this)
    - > Might reduce fuel over-mixing at spray periphery
- Conclusion: DFI shows considerable promise; additional research is justified



# Mixing-Controlled CI Combustion and Fuels Research: Collaborations and Future Work

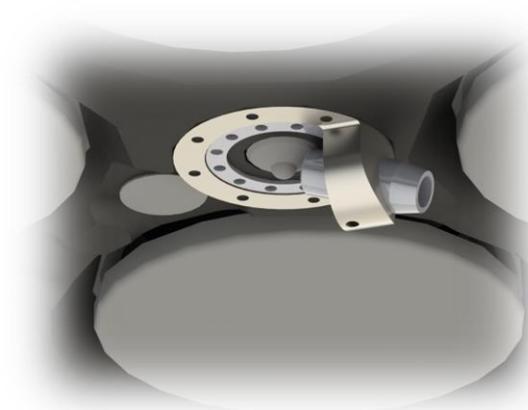


- **Primary Collaborations** (in addition to Co-Optima AED and FP teams)

- DFI CRADA with Caterpillar & Ford (Georgia Tech subcontract)
- Coordinating Research Council (CRC: energy co's, auto OEMs, nat'l labs)
  - > Co-led 2<sup>nd</sup> CRC Advanced Fuels and Engine Efficiency Workshop (Nov. 1-3, 2016)
  - > Co-leading CRC Project AVFL-18a on diesel surrogate fuels for modeling & exp'ts
  - > Member of CRC Fuels for Advanced Combustion Engines (FACE) Working Group
- DOE/NSF project with Yale Univ. on quantifying fuel sooting propensities
- Strategic Partnerships Project with Caterpillar on in-cylinder soot meas'ment
- USCAR Advanced Combustion & Emissions Control LTC Fuels Survey Team
- Modeling origins of HC emissions with San Francisco State Univ.

- **Future Work** *any proposed future work is subject to change based on funding levels*

- Test DFI in the optical engine
  - > Quantify emissions, efficiency, & fuel effects
- Assist with Co-Optima ACI fuel selection and merit function development
- Optical-engine testing of surrogate fuels
- Develop vertical-sheet LII technique to quantify in-cylinder soot



# ANL / NREL / ORNL / SNL (Ickes) \$240k: ACI Engine Merit Function Development & Technical Roll-up

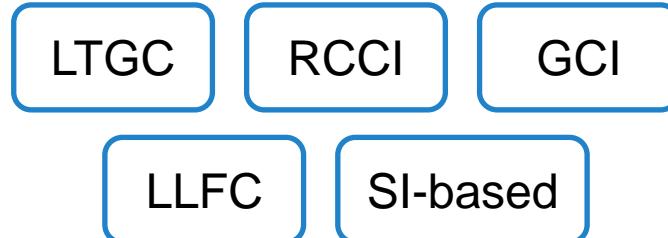


## ● Objective

- Develop a function to show advantageous fuel properties for the suite of ACI combustion concepts to guide ACI engine & fuel co-development

## ● Approach

- Synthesize results from ongoing ACI engine research into fuel property guidance
  - > Highlight key enabling fuel properties for each combustion concept
  - > Relate fuel properties to operating range and efficiency
- Utilize generalized engine performance to create a merit function or functions applicable across the suite of ACI combustion concepts



(Industry solutions may be incorporated based on literature and support/guidance from the responsible organization)

Identify critical fuel properties for operation of specific concept

Specific interest in properties/ranges which preclude operation

Property guidance and merit function to direct ACI engine & fuel co-development



# Collaborations

## **ANL, Ciatti – GCI (Gasoline Compression Ignition)**

- Lund University, Sweden: Collaborate on testing of boosted-SI fuels in GCI engine
- NREL: Provided data to assist in explaining behavior of boosted-SI fuels for GCI

## **SNL, Dec – LTGC (Low-Temperature Gasoline Combustion)**

- ORNL: Collaborate on the development of the core fuel test matrix for boosted-SI engines
- LLNL: Collaborate to apply modeling to search for alternative fuels compatible with LTGC
- GM: Regular meetings to discuss fuel-property research results, e.g. OI & K-factor
- USCAR: Advanced Combustion & Emissions Control LTC Fuels Survey Team

## **ORNL, Curran – RCCI Metal Engine**

- SNL: Collaborate with SNL on compatible metal- and optical-engine studies
- LLNL: Kinetic modeling
- Delphi: Technical discussions on low-temperature combustion
- Univ. of Wisconsin: ACI modeling

## **SNL, Musculus – RCCI Optical Engine**

- ORNL: Collaborate with ORNL on compatible optical- and metal-engine studies
- Wayne State Univ.: Prof. Eagle
- University of Orléans, France: Prof. Mounaïm-Rousselle – collaborative experiments

## **SNL, Mueller – Mixing-Controlled CI Combustion, LLF and DFI**

- DFI CRADA with Caterpillar & Ford (Georgia Tech subcontract)
- Coordinating Research Council (CRC): Multiple projects
- Yale Univ: Quantifying fuel soot propensities of fuels (DOE/NSF project)
- Caterpillar: In-cylinder soot measurements
- USCAR: Advanced Combustion & Emissions Control LTC Fuels Survey Team
- San Francisco State Univ.: Modeling origins of HC emissions

## **ANL, Ickes – Merit Function for ACI Combustion**

- NREL, ORNL & SNL: Work collaboratively to develop Merit Function(s) for ACI



# Response to Reviewers' Comments

- **It is encouraging to see the close collaboration between the national labs.**  
⇒ They appear to be leveraging their individual strengths instead of competing.
  - We thank the reviewers for these positive comments and are glad to hear that the collaborative nature of this project came across in the AMR presentations. We have worked hard from the start to make Co-Optima a highly collaborative effort, with each lab applying its own unique capabilities.
- **Collaborative interactions should also include industrial stakeholders and academia.**
  - Our DOE sponsors have recently funded several university contracts to supplement the work by the labs. Also, similar to our core DOE-VTO work, results of the Co-Optima projects are being reported at the semi-annual AEC meetings, which have strong industrial involvement. Additionally, several of the individual Co-Optima projects have developed interactions with industry as indicated on the Collaborations slide. Results are also shared and discussed at the Co-Optima Stakeholder Meetings.
- **It is critical to test the compatibility of Thrust I fuels on Thrust II engine concepts.**
  - Thrust I, boosted-SI fuels from the core Co-Optima fuels matrix have been tested in both the GCI & LTGC engines. Tests of additional Thrust I fuels from this matrix are planned for the remainder of FY17, extending into FY18 as necessary. The RCCI work is currently using iso-octane as a surrogate for Thrust I fuels.
- **Thrust II projects seem disjointed, and there are no clear metrics to downselect.**
  - It appears that the scope of the Co-Optima effort on Thrust II, ACI projects was not fully explained. The current ACI engine research projects were established prior to Co-Optima, and the majority of the work on the GCI, LTGC, and RCCI projects remains separate from Co-Optima. The Co-Optima effort only involves fuels testing and research toward the development of more optimal fuels, a relatively small fraction of the total work. The mixing-controlled (diesel-like) combustion project has been entirely moved to Co-Optima, but this combustion mode is quite different from the three low-T combustion modes that use gasoline-like fuels.
  - These four projects cover the main approaches to high-efficiency ACI engines. Each has advantages and challenges, and our understanding is insufficient to downselect at this time even if downselecting was within the scope of the Co-Optima effort. Moreover, the best method will likely depend on size class (LD, MD, HD).

# Future Work



*Any proposed future work is subject to change based on funding levels*

## **ANL, Ciatti – GCI (Gasoline Compression Ignition)**

- Improve engine efficiency and BSFC with turbocharger operation and injection strategy
- Endoscope imaging of OH\* chemiluminescence in low HRR region where soot is absent
- PM measurement for GCI soot characteristics

## **SNL, Dec – LTGC (Low-Temperature Gasoline Combustion)**

- Complete evaluation of E30, including  $\phi$ -sensitivity and high loads studies
- Evaluate the other three fuels in the test matrix: High-Olefin, High-Cycloalkane & Alkylate
- Investigate Co-Optima fuels with good potential for full-time LTGC-ACI engines
- Support ACI merit function development

## **ORNL, Curran – RCCI Metal Engine**

- Identify dual fuels for RCCI w/ matched chemical properties but different physical properties
- Investigate RCCI performance using these fuel pairs

## **SNL, Musculus – RCCI Optical Engine**

- Conduct laser-sheet imaging studies to quantify mixing effects for the PRF fuel combinations
- Image combustion phenomena for ORNL fuels with different physical properties

## **SNL, Mueller – Mixing-Controlled CI Combustion, LLF and DFI**

- Test DFI in the optical engine  $\Rightarrow$  Quantify emissions, efficiency and fuel effects
- Assist with Co-Optima ACI fuel selection and merit function development
- Optical-engine testing of surrogate fuels
- Develop vertical-sheet LII technique to quantify in-cylinder soot

## **ANL, Ickes – Merit Function for ACI Combustion**

- Work collaboratively with NREL, ORNL & SNL to develop Merit Function(s) for ACI

# Summary of Exploratory ACI Combustion Tasks



## Relevance

- Understanding fuel effects on the various ACI combustion modes is central to the development and deployment of high-efficiency ACI engines

## Approach

- Individual projects leverage core DOE-VTO research programs and facilities, and they build on the strengths of the various national laboratories

## Accomplishments – Strong technical progress has been made in the areas of:

- Demonstrating GCI combustion using “boosted-SI” fuels, and investigating the effects of these fuels on performance and emissions.
- Determining the effects of “boosted-SI” fuels on LTGC-engine performance, and evaluating the adequacy of RON & MON as metrics for the Central Fuel Hypothesis for these engines.
- Evaluating the range of control authority for iso-octane (as a surrogate for “boosted-SI” fuels) in combination with n-heptane in an RCCI engine.
- Showing that optical-engine and metal-engine performance correlate, and visualizing the differences in combustion behavior for the three regimes of RCCI combustion.
- Demonstrating Ducted Fuel Injection (DFI) as an effective method for substantially reducing soot formation during mixing-controlled CI combustion.

## Collaborations

- As listed on the Collaborations Slide, each project has a significant number of collaborations.  
⇒ Collaborations include industry and universities, as well as other national labs.
- Results presented at AEC semi-annual Working Group Meetings, engaged with ACEC TT

## Future Work (*Any proposed future work is subject to change based on funding levels*)

- As listed on the Future Work Slide, a portfolio of future work has been described.



# Acknowledgement

- The work on Tasks E2.1.2, E2.2.2, and E2.2.3 (Slides 8 – 10, 15 – 19, and the work attributed to SNL on slides 11 and 14) was performed at the Combustion Research Facility, Sandia National Laboratories, Livermore, CA.

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## Reviewer Only Slides



# Publications and Presentations – 1

## ANL, Ciatti – GCI (Gasoline Compression Ignition)

- Ciatti, S. and Cung, K., "Performance of High RON Fuels in a Multi-Cylinder Engine at GCI Operating Conditions," DOE Advanced Engine Combustion Working Group Meeting, January 2017.
- Ciatti, S. and Cung, K., "Performance of High RON Fuels in a Multi-Cylinder Engine at GCI Operating Conditions," Oral only presentation at the SAE World Congress, April 2017.

## SNL, Dec – LTGC (Low-Temperature Gasoline Combustion)

- Dec, J.E., Dernotte, J., and Ji, C., "Fuel Effects on LTGC Combustion – Initial Results for a Co-Optima Fuel," GM/Sandia Working Group Meeting, August 2016.
- Dec, J.E., Ji, C., and Gentz, G., "Additional Evaluation of Co-Optima Fuels," GM/Sandia Working Group Meeting, April 2017.

## ORNL, Curran – RCCI Metal Engine

- Dempsey, A.B, Curran, S.J., and Wagner, R.M., "A perspective on the range of gasoline compression ignition combustion strategies for high engine efficiency and low NOx and soot emissions: Effects of in-cylinder fuel stratification", 2016, *International Journal of Engine Research*, DOI: 10.1177/1468087415621805.
- Wissink, M et al., " Performance and emissions of RCCI with iso-octane and n-heptane on a light-duty multi-cylinder engine," DOE Advanced Engine Combustion Working Group Meeting, January 2017.
- Wissink, M et al., " Performance and emissions of RCCI with iso-octane and n-heptane on a light-duty multi-cylinder engine," Oral only presentation at the SAE World Congress, April 2017.
- Wissink, M., et al., "Extending RCCI Load Limits," presented at Co-Optima Stakeholders Meeting, March, 2017.
- Wagner, M., "Pushing the efficiency of internal combustion engines and UAV", 2017 UAV Israel, Jan 2017.
- Wagner, M., "Reactivity Stratified Combustion and Future Fuel", KAUST Combustion Conference, March 2017.
- Wagner, M., "Directions in High Efficiency Engine Research and Future Fuel Opportunities," Centennial Seminar Series, Missouri University of Science and Technology, August 2016.
- Curran, S., Wagner, R., "Reactivity Stratified Combustion Development for Light-Duty Multi-Cylinder Engines" IEA Technology Collaboration Programmes (TCP) for Clean and Efficient Combustion, 38th Task Leaders Meeting, Ruka, Finland, June 2016.

## SNL, Musculus – RCCI Optical Engine

- Eagle, W.E. and Musculus, M.P.B., "Optical imaging to understand fuel reactivity effects on RCCI combustion," DOE Advanced Engine Combustion Working Group Meeting, August 2016.



# Publications and Presentations – 2

## SNL, Mueller – Mixing-Controlled CI Combustion and Fuels Research

- **Publications**

1. Mueller, C.J., Nilsen, C.W., Ruth, D.J., Gehmlich, R.K., Pickett, L.M., and Skeen, S.A., "Ducted Fuel Injection: A New Approach for Lowering Soot Emissions from Direct-Injection Engines," *Applied Energy*, submitted March 21, 2017.
2. Cheng, A.S. and Mueller, C.J., "Conceptual Investigation of the Origins of Hydrocarbon Emissions from Mixing-Controlled, Compression-Ignition Combustion," *SAE Int. J. Engines* **10**(3), 2017, doi:10.4271/2017-01-0724.
3. Das, D.D., McEnally, C.S., Kwan, T.A., Zimmerman, J.B., Cannella, W.J., Mueller, C.J., and Pfefferle, L.D., "Sooting Tendencies of Diesel Fuels, Jet Fuels, and Their Surrogates in Diffusion Flames," *Fuel* **197**:445-458, 2017, doi:10.1016/j.fuel.2017.01.099.
4. Das, D.D., Cannella, W.J., McEnally, C.S., Mueller, C.J., and Pfefferle, L.D., "Two-Dimensional Soot Volume Fraction Measurements in Flames Doped with Large Hydrocarbons," *Proc. Combust. Inst.* **36**(1):871–879, 2017, doi:10.1016/j.proci.2016.06.047.
5. Mueller, C.J., "Improved Mixing-Controlled Combustion Technologies and Fuels for High-Efficiency Compression Ignition Engines," *Proc. of DOE Advanced Engine Combustion and Fuels Program Review*, DOE Office of Vehicle Technologies Annual Report, 2016.
6. Dumitrescu, C.E., Cheng, A.S., Kurtz, E., and Mueller, C.J., "A Comparison of Methyl Decanoate and Tripropylene Glycol Monomethyl Ether for Soot-Free Combustion in an Optical Direct-Injection Diesel Engine." ICEF2016-9366, 2016 ASME Internal Combustion Engine Fall Technical Conference, Greenville, SC, Oct. 9-12, 2016. American Society of Mechanical Engineers. 2016.
7. Gehmlich, R.K., Dumitrescu, C.E., Wang, Y., and Mueller, C.J., "Leaner Lifted-Flame Combustion Enabled by the Use of an Oxygenated Fuel in an Optical CI Engine," *SAE Int. J. Engines* **9**(3), 2016, doi:10.4271/2016-01-0730.

- **Presentations**

- 16 presentations from this project since last DOE Annual Merit Review (AMR) meeting, 3 invited.

- **Patents**

- Non-provisional appl. #15,363,966: "Ducted Fuel Injection" filed Nov. 29, 2016.
  - Non-provisional appl. #15,364,002: "Ducted Fuel Injection with Ignition Assist" filed Nov. 29, 2016.

- **Award**

- Coordinating Research Council (CRC) Advanced Vehicles, Fuels, and Lubricants (AVFL) Committee Special Recognition Award (Feb. 7, 2017).