

# Ducted Fuel Injection (DFI) for Heavy-Duty Engines

SAND2019-4725PE



**Charles J. Mueller**

Sandia National Laboratories

Engine Combustion Research Department

Livermore, California

*Funded by: U.S. Dept. of Energy, Vehicle Technologies Office  
Program managers: Michael Weismiller & Gurpreet Singh*



**DOE Vehicle Tech. Office Annual Merit Review Mtg.**

Hyatt Regency Crystal City, Arlington, Virginia

June 13, 2019 @ 9:00 am

Project ID: ACE131

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SAND2019-XXXX-X

# Overview

## Timeline

- Project start: Oct. 1, 2018
- Project end: Sept. 30, 2019
- 56% complete

## Budget

- FY19 funding: \$550k
  - Mueller: \$450k
  - Skeen: \$100k
- FY18 funding: \$0k

*FY = fiscal year, runs Oct. 1 – Sept. 30; NO<sub>x</sub> = nitrogen oxides; PI = principal investigator; MOU = Memorandum of Understanding; Co-Optima = Co-Optimization of Fuels and Engines program; CRADA = Cooperative Research & Development Agreement*

## Barriers

- “The research areas of highest priority for clean diesel combustion are:
  - a. Reduced engine-out NO<sub>x</sub> and particulate emissions
  - b. ...”

\*from [https://www.energy.gov/sites/prod/files/2018/03/f49/ACEC\\_TT\\_Roadmap\\_2018.pdf](https://www.energy.gov/sites/prod/files/2018/03/f49/ACEC_TT_Roadmap_2018.pdf), Page 2.

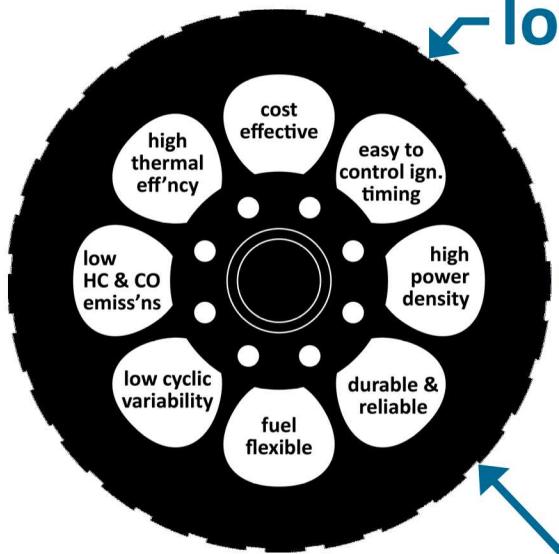
## Partners

- PI: Charles J. Mueller
- Co-Optima
- Caterpillar & Ford (CRADA)
- Advanced Engine Combustion MOU

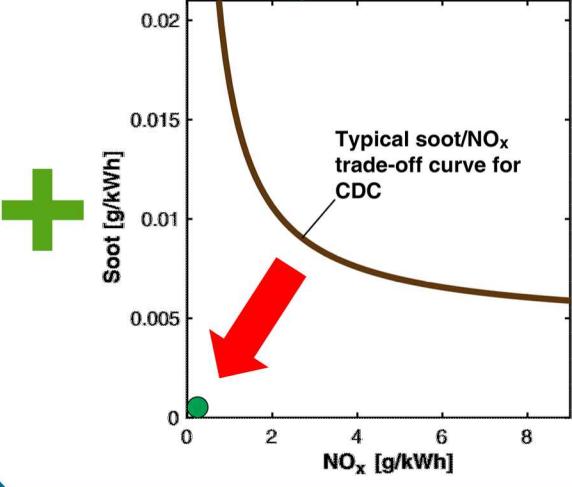
# Relevance

"The U.S. Department of Energy's Vehicle Technologies Office provides **low cost**, **secure**, and **clean** energy technologies to move people and goods across America." <https://www.energy.gov/eere/vehicles/vehicle-technologies-office>

Our objective: Maintain all the desirable attributes of conventional diesel combustion (CDC)...



low cost      clean



Co-Optima  
(see FT077)



...with 10X – 100X lower soot & NO<sub>x</sub> emissions

...while harnessing synergies with secure, domestic fuels.

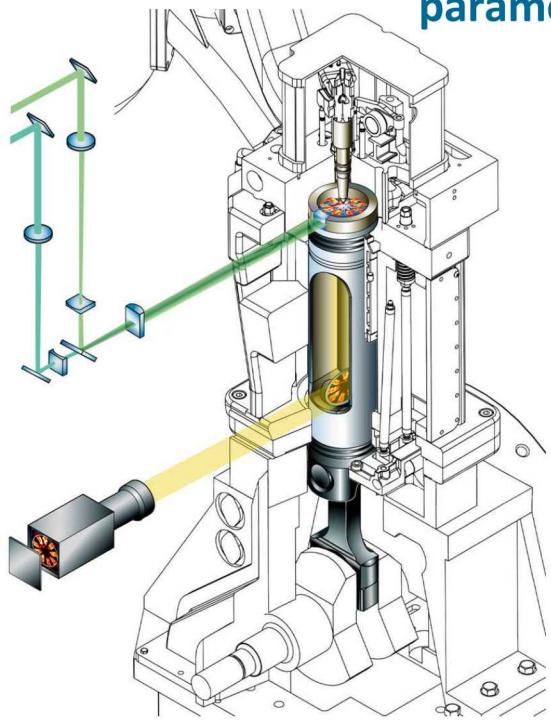
# Milestones

- **Dec. 31, 2018:** Install & align DFI two-duct holder in optical engine, and complete testing to determine whether DFI can break the soot/NO<sub>x</sub> trade-off with conventional diesel fuel.
  - Completed.
- **Sept. 30, 2019:** Determine sensitivity of DFI to changing four engine operating-condition and/or fuel-injection parameters.
  - On track.

# Approach

Designed to provide stakeholders with high-quality, relevant, unbiased experimental data for making informed decisions regarding DFI technology.

Using the **only DFI engine in the world** & guidance from industry, conduct sweeps of basic engine operating-condition & fuel-injection parameters to better understand **sensitivities**.



- **Swept variables**

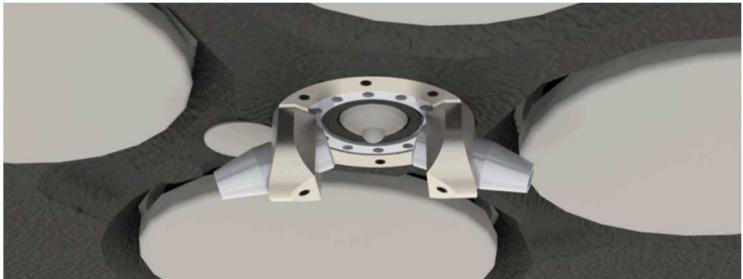
- Intake oxygen mole fraction,  $X_{O_2}$
- Duration of injection, DOI
- Start of combustion, SOC
- Injection pressure,  $P_{inj}$
- Intake manifold abs. press., IMAP
- Intake manifold temperature, IMT

- **Diagnostics**

- Cylinder pressure
- Emissions
- Natural luminosity (NL) imaging

# Technical accomplishments

# Successfully installed & aligned a two-duct holder to test DFI in the optical engine

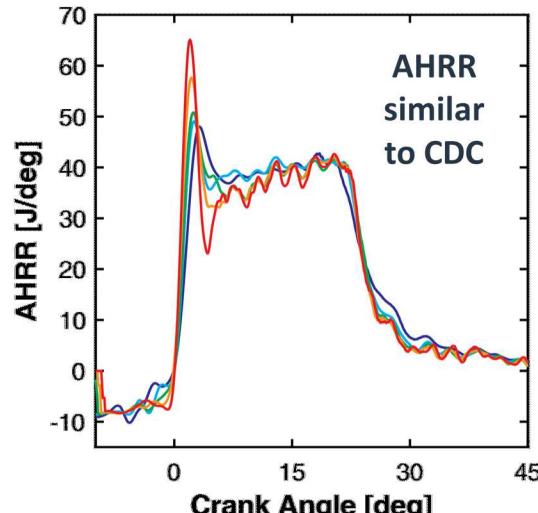
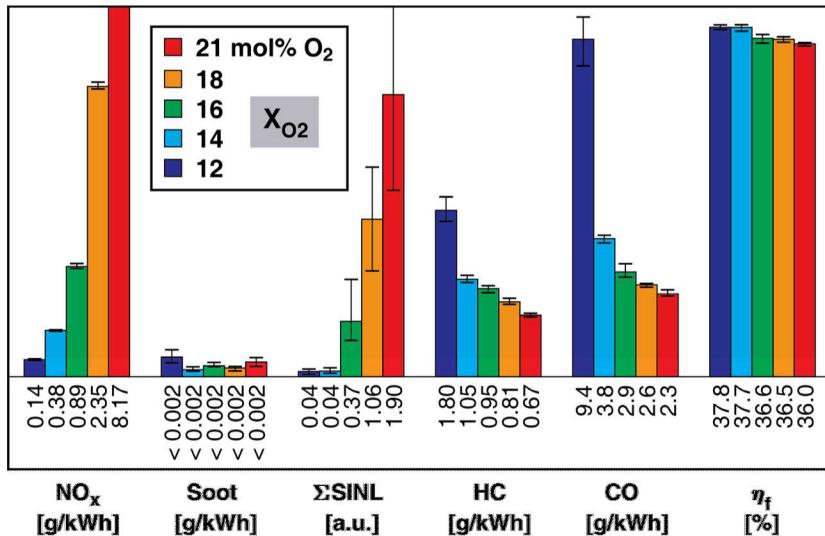


- **Duct configuration**
  - 2 mm inner diam., 12 mm long, inlet 3 mm from inj. orifice exit
- **Injector tip**
  - $2 \times 0.108 \text{ mm} \times 140^\circ$
  - Results in  $\sim 2.6 \text{ bar}$  gross IMEP
- **Fuel**
  - No. 2 S15 certification diesel
- **1200 rpm engine speed**

Research engine	Single-cyl.
Cycle	4-stroke CI
Valves per cylinder	4
Bore	125 mm
Stroke	140 mm
Displacement per cylinder	1.72 liters
Conn. rod length	225 mm
Conn. rod offset	None
Piston bowl diameter	90 mm
Piston bowl depth	16.4 mm
Squish height	1.5 mm
Swirl ratio	0.59
Compression ratio	12.5:1
Simulated compr. ratio	16.0:1

*IMEP = indicated mean effective pressure; S15 = 15 parts per million sulfur max.; CI = compression ignition*

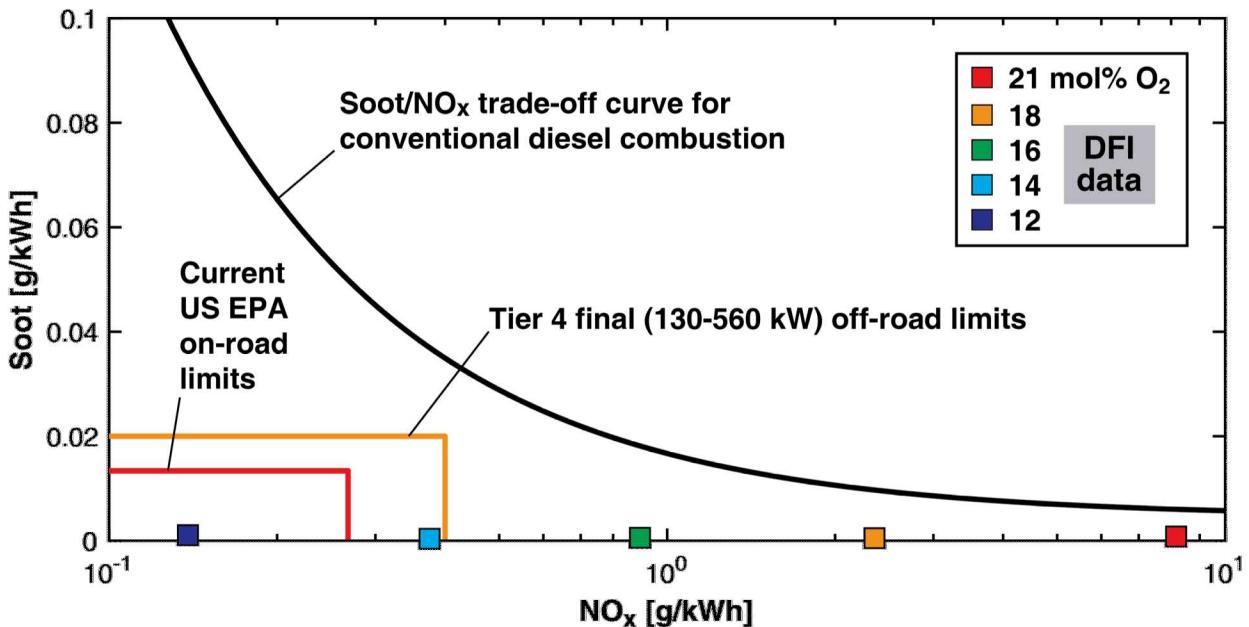
# Intake oxygen mole fraction ( $X_{O_2}$ ) sweep shows benefits of DFI with dilution.



- $NO_x$  is dramatically  $\downarrow$  without a corresponding soot  $\uparrow$
- HC & CO emissions  $\uparrow$  more significantly at highest dilution
- Fuel-conversion efficiency ( $\eta_f$ ) improves with dilution

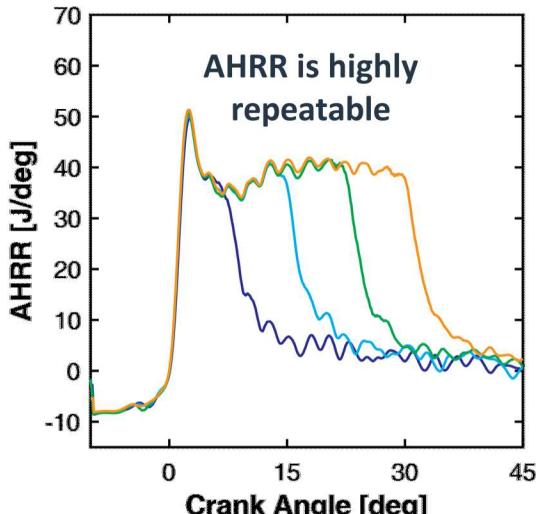
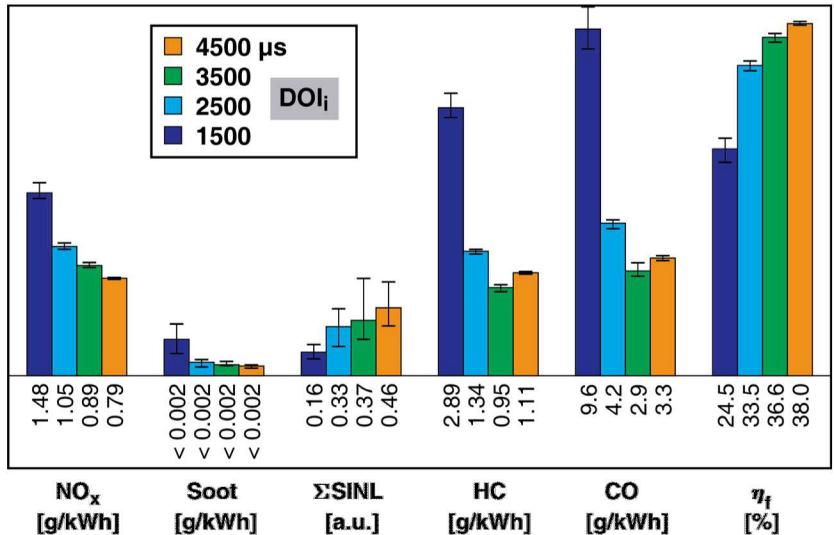
$O_2$  = molecular oxygen;  $\Sigma SINL$  = temporally & spatially integrated natural luminosity (indicator of hot, in-cylinder soot); HC = hydrocarbon; CO = carbon monoxide; AHRR = apparent heat-release rate

# DFI with dilution can break the long-standing diesel soot/NO<sub>x</sub> trade-off.



- DFI lowers soot by ~10X to ~100X with current diesel fuel
- Dilution lowers NO<sub>x</sub> by ~20X to ~50X

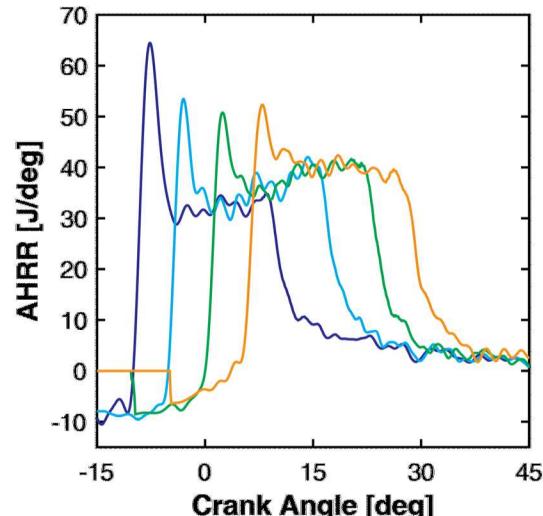
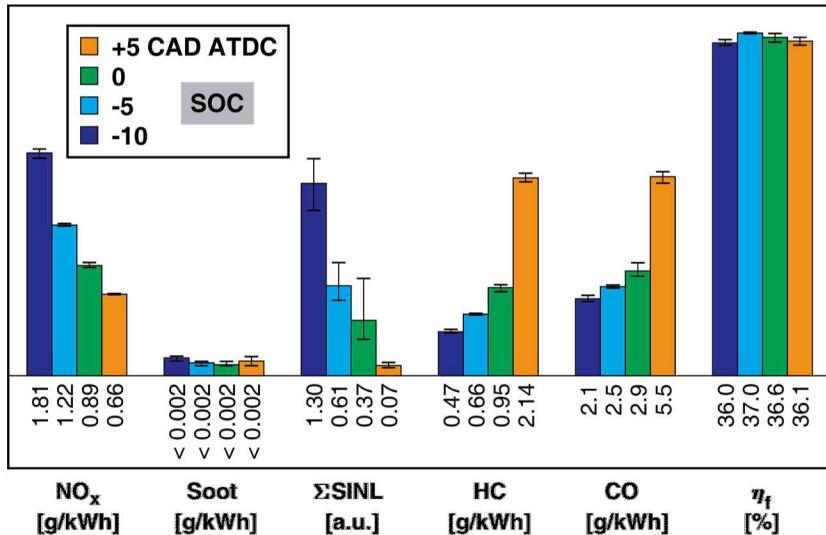
# Duration of injection (DOI) sweep shows that longer injections tend to be better.



- Longer DOIs tend to produce lower indicated-specific NO<sub>x</sub>, HC, & CO emissions, as well as higher  $\eta_f$

$DOI_i$  = indicated duration of injection (i.e., duration of electronic trigger signal to injector driver)

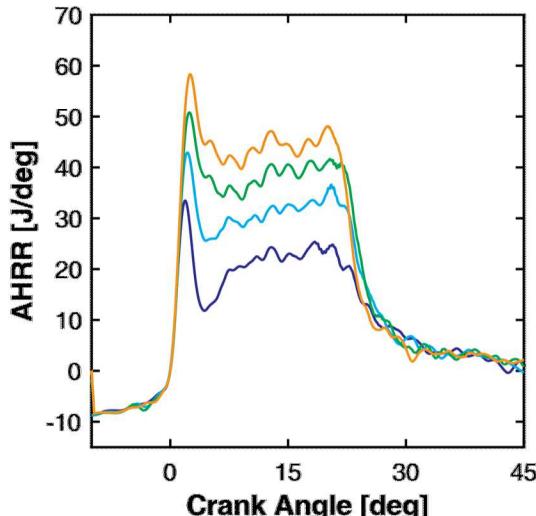
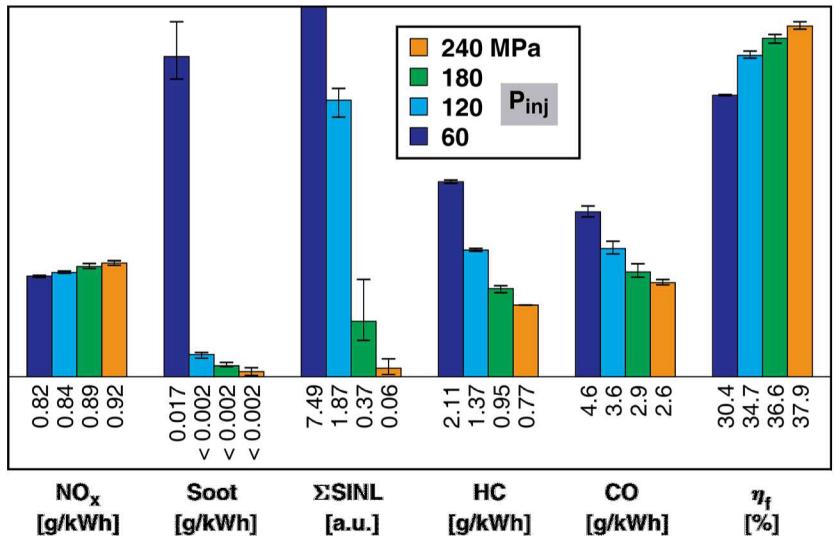
# Start of combustion (SOC) sweep shows that DFI behaves similarly to CDC.



- Retarding SOC causes NO<sub>x</sub> ↓, HC & CO ↑
  - Also facilitates transition to LLFC (indicated by low  $\Sigma$ SINL)
- $\eta_f$  does not change significantly for the studied SOC range

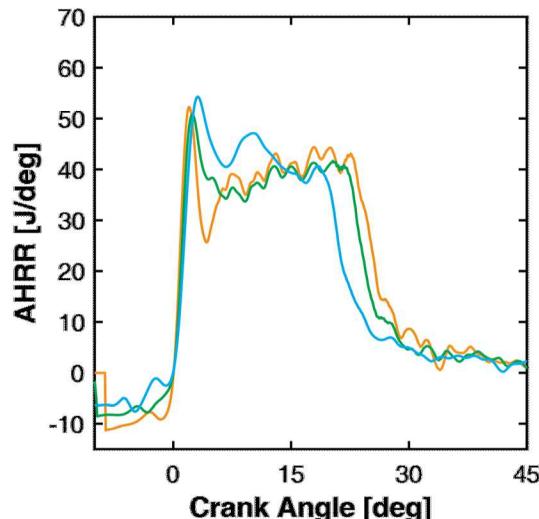
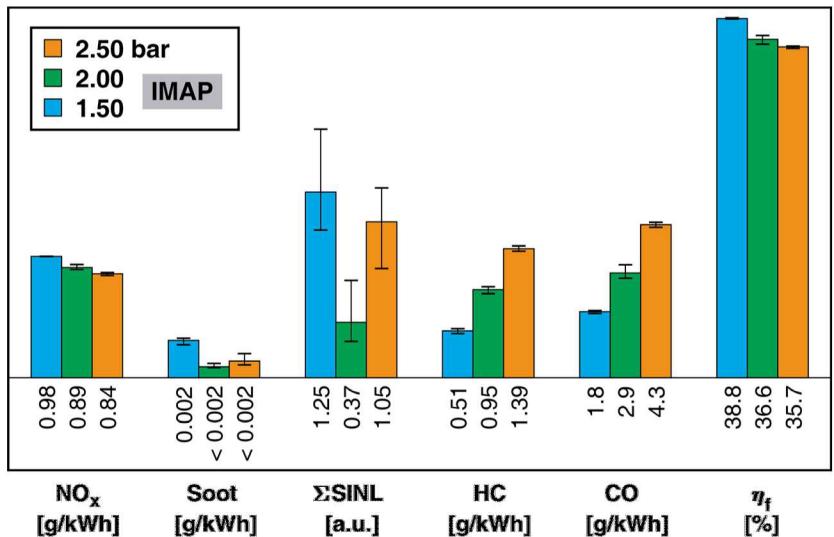
LLFC = leaner lifted-flame combustion (i.e., diesel combustion that does not produce soot); CAD ATDC = crank-angle degrees after top-dead-center

# Injection pressure ( $P_{inj}$ ) sweep shows that higher $P_{inj}$ is largely beneficial.



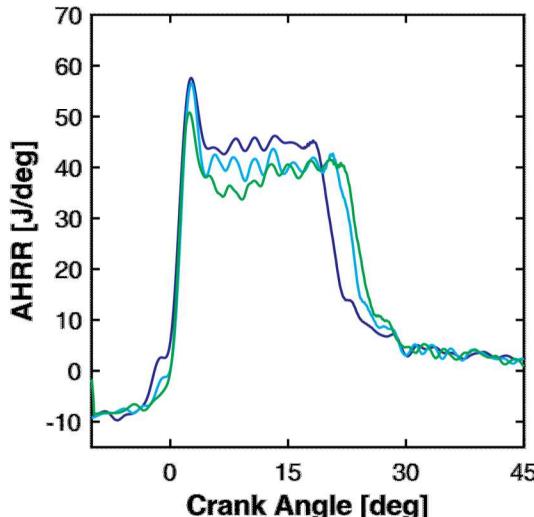
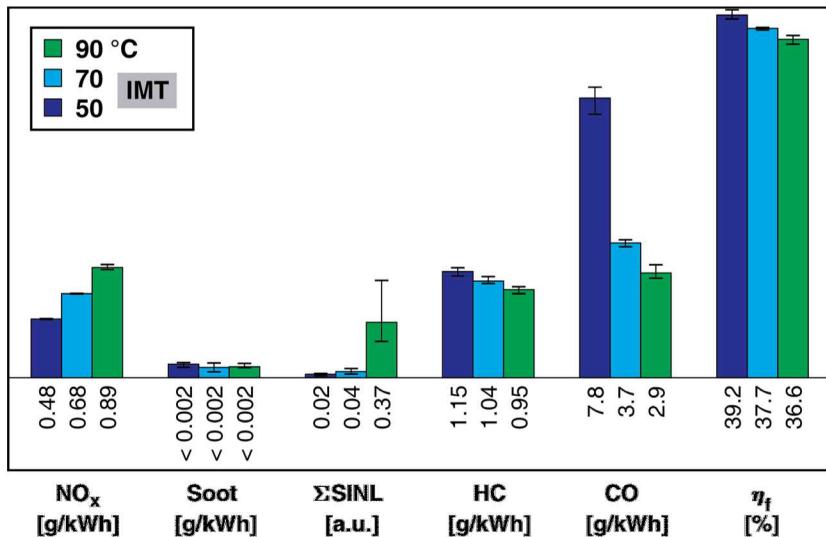
- Soot, HC, CO, &  $\eta_f$  all improve as  $P_{inj}$   $\uparrow$ 
  - Highest  $P_{inj}$  of 240 MPa intermittently achieves LLFC
- Measureable soot can be produced if  $P_{inj}$  is too low

# Intake manifold abs. pressure (IMAP) sweep: lower IMAP is generally better.



- HC, CO, &  $\eta_f$  all improve as IMAP  $\downarrow$ 
  - But NO<sub>x</sub> & soot degrade slightly
- Local minimum in  $\Sigma$ SINL at 2.00 bar IMAP baseline condition requires further study

# Intake manifold temperature (IMT) sweep shows mixed results.



- NO<sub>x</sub>, ΣSINL, & η<sub>f</sub> all improve as IMT ↓
  - Should be beneficial for low NO<sub>x</sub> under cold-start operation
  - LLFC intermittently achieved at 50 °C IMT
- HC & CO ↑ somewhat as IMT ↓

# Responses to previous year's reviewers' comments

- No reviewer comments – this project was a new start in FY19.

# Collaboration & coordination with other institutions

- **Co-Optimization of Fuels & Engines Program (Co-Optima)**
  - Two (2) DOE offices, nine (9) national labs, > 20 universities, > 80 stakeholder organizations, > 120 researchers
  - Fuel effects on DFI
- **DOE Technology Commercialization Fund CRADA**
  - Partners: Caterpillar Inc. & Ford Motor Co.
  - Two-year project, started in FY19
  - Overcoming barriers to DFI commercialization
- **Advanced Engine Combustion MOU**
  - 18 companies, 20 universities, seven (7) national labs
  - General guidance & oversight
- **Sibendu Som (Argonne National Lab) & Sotirios Mamalis (Stony Brook University): Large eddy simulations of DFI**

# Remaining challenges & barriers

- **What is the potential for DFI to work at high load cond's?**
  - What are the effects of adding more ducts &/or using larger injector-orifice diameters?
- **How sensitive is engine-DFI performance to varying duct geometric parameters?**
  - E.g., duct inside diameter, duct length, & stand-off distance from injector-orifice exit plane to duct inlet plane
- **What are the fundamental physical processes governing DFI performance?**
  - How can they be used to determine optimal duct designs?
- **How can the slight drop in thermal efficiency be reversed?**
- **What is required to ensure duct alignment & durability?**

# Proposed future research (rest of FY19 & FY20)

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

- Explore strategies for achieving **high load DFI operation**
  - Adding more ducts (six if possible, otherwise four)
  - Using larger injector-orifice diameters ( $\sim \varnothing.175$  mm)
- Quantify sensitivity of engine-DFI performance to **varying duct geometric parameters**
  - Duct inside diameter ( $\varnothing 2$  mm vs.  $\varnothing 3$  mm)
  - Length (8 mm vs. 12 mm vs. 16 mm)
- Develop an improved understanding of the **fundamental physical processes** governing DFI performance
  - Use existing literature, theoretical analysis, & computational investigations

# Summary

<b>Relevance</b>	This research directly supports the DOE Vehicle Technologies Office mission of providing “low cost, secure, and clean energy technologies to move people and goods across America” & a key industry objective of simultaneously lowering diesel NO <sub>x</sub> & soot.
<b>Approach</b>	<ul style="list-style-type: none"><li>Conducted the world’s first DFI experiments in an engine.</li><li>All milestones are either completed or on track.</li></ul>
<b>Technical accomplishments</b>	<ul style="list-style-type: none"><li>Tested DFI while sweeping X<sub>O<sub>2</sub></sub>, DOI, SOC, P<sub>inj</sub>, IMAP, &amp; IMT.</li><li>DFI with dilution can break the long-standing diesel soot/NO<sub>x</sub> trade-off, potentially enabling a new generation of clean, cost-effective engines that are compatible with current fuels.</li><li>In many regards, DFI performs similarly to CDC, except with substantially lower soot emissions.</li></ul>
<b>Collaboration &amp; coordination</b>	The work is closely integrated with Co-Optima, the Advanced Engine Combustion MOU, & industry through a CRADA.
<b>Future research</b>	Addresses key technical barriers to DFI implementation: increasing load, understanding duct-geometry sensitivities, & optimizing performance for different applications.

# Technical back-up slides

# Reviewer-only slides

# Publications & presentations

## Journal & conference publications

1. Nilsen, C.W., Biles, D.E., & Mueller, C.J., "Using Ducted Fuel Injection to Attenuate Soot Formation in a Mixing-Controlled Compression-Ignition Engine," *SAE Int. J. Engines*, in press, Mar. 2019.
2. Yasutomi, K., Mueller, C.J., Pickett, L.M., & Skeen, S.A., "Investigation of the spray and combustion characteristics of four multi-component diesel surrogate fuels relative to their commercial target fuel," *THIESEL 2018 Conference on Thermo- and Fluid Dynamic Processes in Direct Injection Engines*, Valencia, Spain, Sept. 11-14, 2018.
3. Gehmlich, R.K., Mueller, C.J., Ruth, D.J., Nilsen, C.W., Skeen, S.A., & Manin, J., "Using Ducted Fuel Injection to Attenuate or Prevent Soot Formation in Mixing-Controlled Combustion Strategies for Engine Applications," *Applied Energy* **226**:1169-86, doi:10.1016/j.apenergy.2018.05.078, 2018.

## Other publications/releases

*DOE Vehicle Technologies Office FY 2018 Annual Progress Report, Advanced Combustion Systems and Fuels; U.S. DRIVE Highlights of Technical Accomplishments; Co-Optimization of Fuels & Engines FY18 Year in Review; Sandia FY18 Partnerships Annual Report; Sandia National Laboratories Intellectual Property Video: "Ducted Fuel Injection,"* <https://ip.sandia.gov/technology.do/techID=201>.

## Patents

1. Mueller, C.J., "Ducted Fuel Injection," US Patent #10,161,626; issued Dec. 25, 2018.
2. Mueller, C.J., "Ducted Fuel Injection with Ignition Assist," US Patent #10,138,855; issued Nov. 27, 2018.

**Presentations:** 36 from this project since 2018 DOE Annual Merit Review meeting, two invited.

# Critical assumptions & issues

- The potential barriers to the commercial implementation of DFI can be overcome, including:
  - Duct durability (thermal/mechanical fatigue, deposits)
  - Full-load operation (scaling to more ducts & larger orifices)
  - Spray/duct alignment (establishing & maintaining over life)
  - Combustion noise (maintaining within established limits)
  - Cold-start performance (maint'ing stability & low emiss'ns)
  - Thermal efficiency loss (modify combust. chamber design?)
  - Limited physical understanding (how to optimize?)
- Optical-engine results are adequately representative of results from production/metal engines
- Full electrification will not replace internal-combustion engines in the off-road sector before DFI is implemented