Project ID: ace163

Ducted Fuel Injection and Cooled Spray Technologies for Particulate Control in Heavy-Duty Diesel Engines

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2022 DOE Vehicle Technologies office annual merit review

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

Wabtec CORPORATION

Project Overview

Timeline

- Start: October 2020
- End: ~~December 2023~~ ➔ February, 2024
- ~35% complete

Partners

- Sandia National Laboratories
- Southwest Research Institute

Budget

- Total Project Funding: $3.1MM over 3 years
  - DOE: $2.4MM
  - Wabtec: $641k
- Total project funds for Year 2: $1MM

Barriers

- Off-road vehicles use complex emission control devices to meet regulations.
- Technologies are needed that increase efficiency and/or reduce cost, complexity and energy penalty associated with emissions control over a typical drive cycle.

Relevance

Impact

- Ducted fuel injection (DFI) and Cooled spray (CS) have shown >70% particulate matter (PM) reductions at some conditions

➔ Emissions solutions with improved simplicity, cost, and efficiency

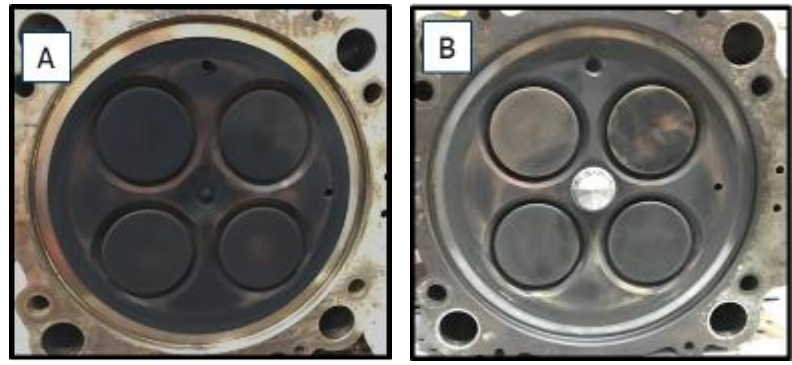
Objectives

- Develop scaling rules to apply DFI/CS
- 75% Particulate Matter reduction over operating range using CS technology

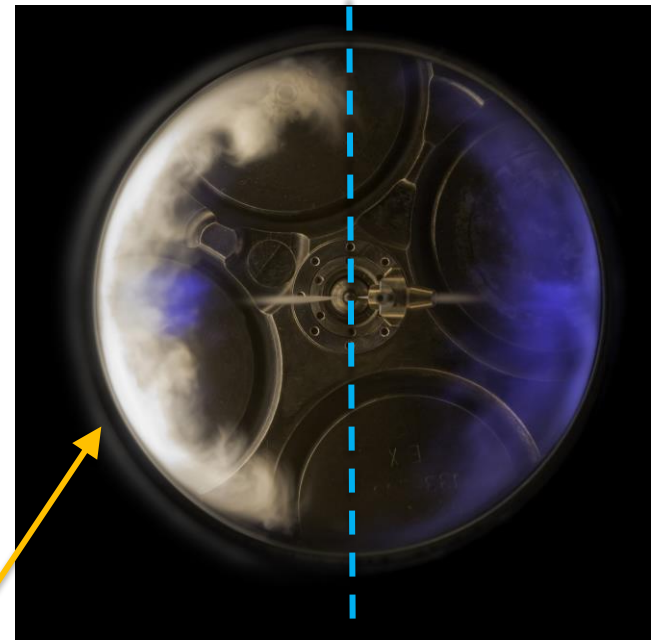
2021 Objectives

- Design/Build hardware
- Baseline engines and preliminary tests of CS/DFI

Conventional Diesel Combustion | With Cooled Spray



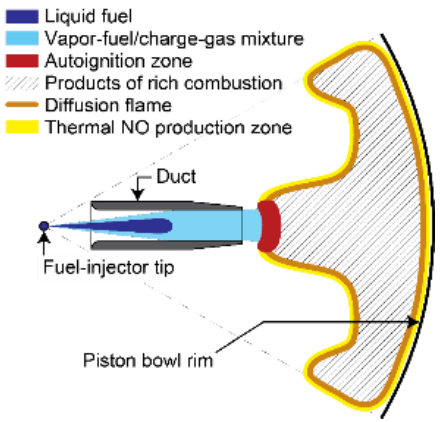
Conventional Diesel Combustion | Ducted Fuel Injection

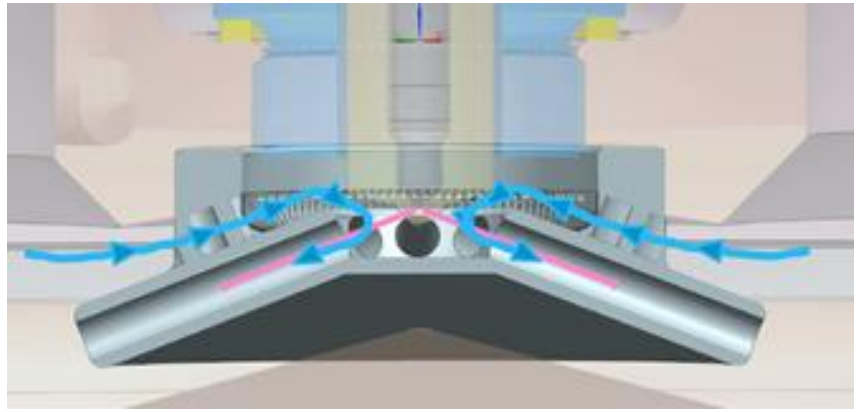


Yellow Flame
➔Soot

Responses to Previous Year Reviewers' Comments

Could the project team describe what the CS concept is doing that is inherently different in the near nozzle region from DFI.





DFI:

- One duct per nozzle hole
- Excellent for fundamental studies

Cooled Spray:

- All fuel and air passages packaged into one component
- Designed for durability, retrofitability, compatibility with production engine hardware

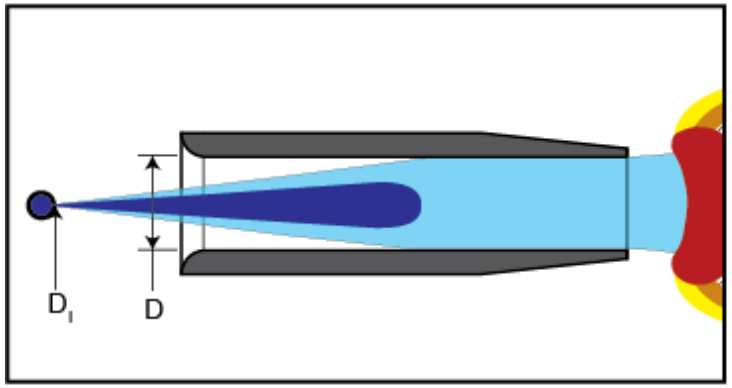
Learnings from DFI can be used to guide some geometry selection for CS

Approach

Question: How to make this work in a larger/smaller engine?

Optical Engine: Develop scaling rules for DFI/CS

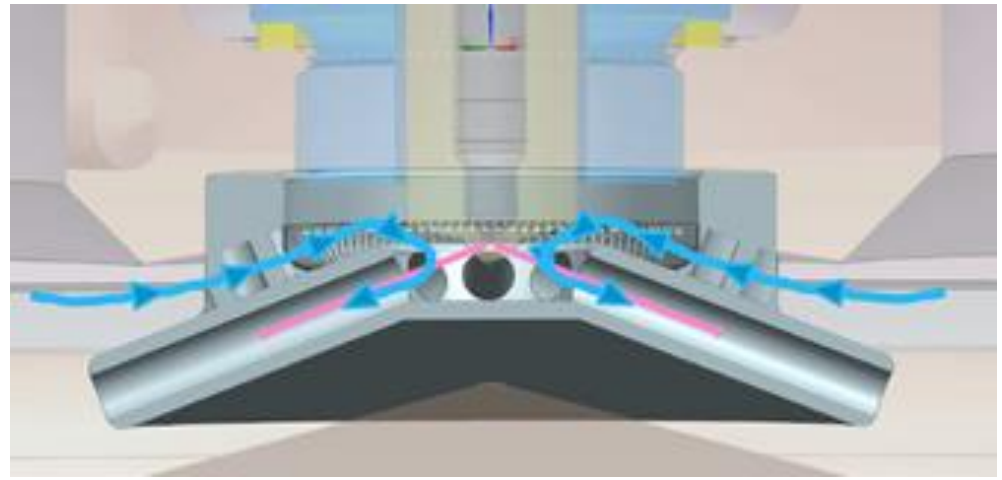
- Vary injector hole size over wide range
- Characterize DFI/CS geometry sensitivity
- Up to 200 bar cylinder pressure
- Orifice diameter relative to duct diameter
    - 173, 225, 275 µm orifices



Question: How well does this perform in a real engine?

Metal Engine: 75% Particulate Matter (Soot) reduction

- 6-hole injector, Up to 24Bar BMEP
- Cooled Spray in single-cylinder engine
- Design features guided by optical engine results
- Evaluate over engine map



Milestones

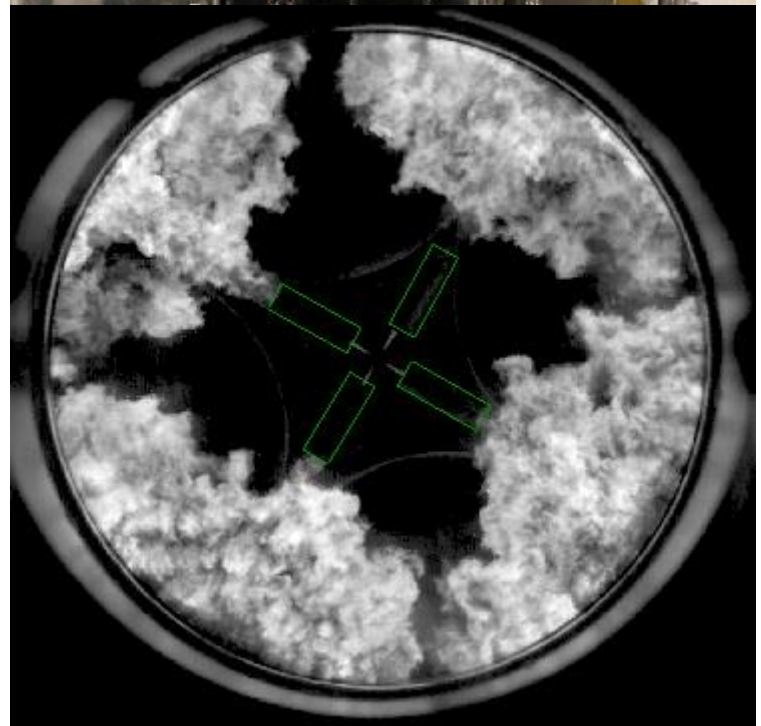
Date	Status	Description
Dec, 2021*	Complete	**M1.3**: Characterize performance for base engine design with and without EGR at key operating conditions.
Dec, 2021	Complete	**M1.4**: Fuel injector and custom nozzles, custom cylinder head, DFI components and CS blanks designed and procurement initiated.
Feb 2022	Complete	**G1**: Optical engine built and ready for commissioning. Metal engine commissioned and baseline performance tests run over 13 operating conditions.
Mar, 2022*	Complete	**M1.5**: DFI evaluated in the optical engine for the new hardware.
Sep, 2022	In Progress	**M2.1**: Generate updated CS geometries for metal engine testing based on previous metal and optical engine tests.
Dec, 2022	On Schedule	**M2.2**: Performance results in at least 2 updated CS designs for at least 3 conditions.
Feb 2023	On Schedule	**G2**: At least 50% soot reduction observed for some conditions in the metal SCE using production-capable fuel injector
Mar, 2023	On Schedule	**M2.3**: Downselection of CS hardware and broad performance sweep using CS.
Mar, 2023	On Schedule	**M2.4**: Evaluation of CS design in optical engine and comparison to DFI completed.
Jun, 2023	On Schedule	**M3.1**: Detailed analysis of optical and metal engine test results and summary of key scaling factors.
Oct, 2023	On Schedule	**M3.2**: Update CS hardware for metal engine tests with focus on improving difficult operating conditions.

*Milestone was completed behind schedule

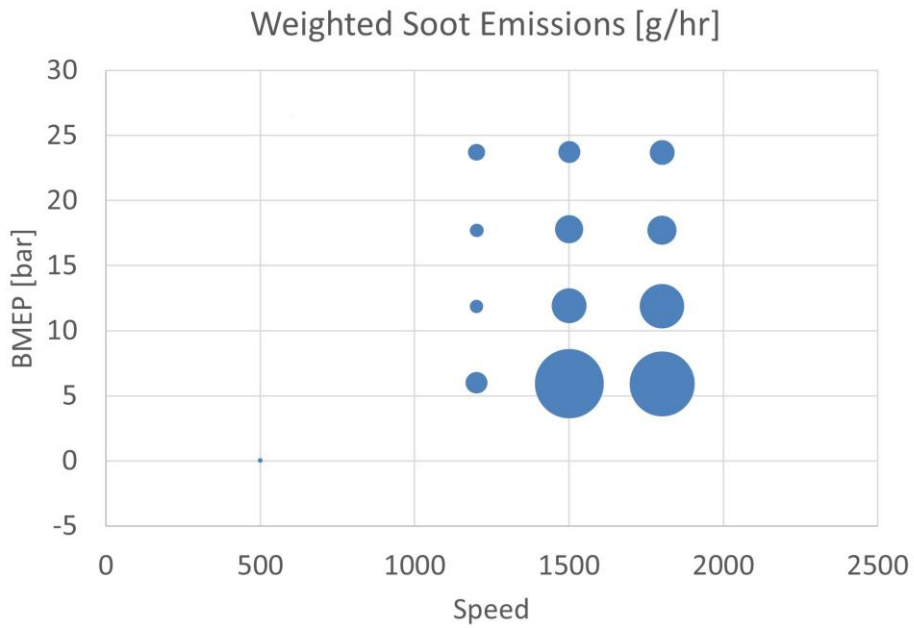
Technical accomplishments and progress

Optical engine

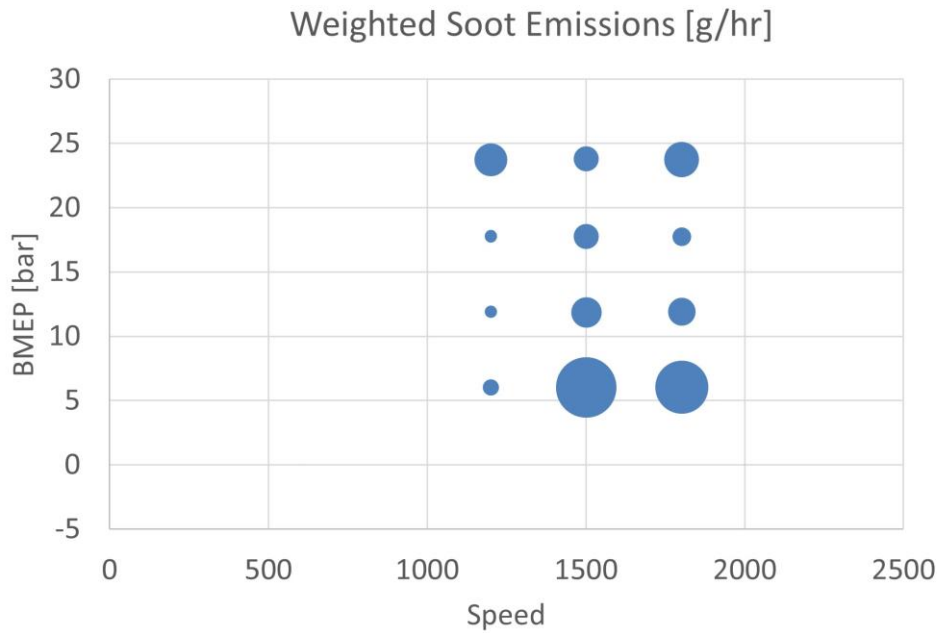
- Hardware manufactured and installed (**Milestone 1.4, Go/No-Go 1**)
    - *Cylinder head*
    - *Fuel-injection system*
        - *Injector driver*
        - *Fuel injector*
    - *Data acquisition system*
    - *DFI/CS mounting and alignment stage*
- Titanium alloy piston body manufactured
- Engine tested up to 10 Bar IMEP of conventional diesel combustion (CDC) and DFI configurations (**Milestone 1.5**)



Technical Accomplishments and Progress: SCE Engine Baselining (Milestone 1.3, Go/No-Go 1)



Nozzle 1: 0.32mm orifice
Duty Cycle Emissions:
NOx 6.72 g/kW-hr
Soot: 0.07g/kW-hr

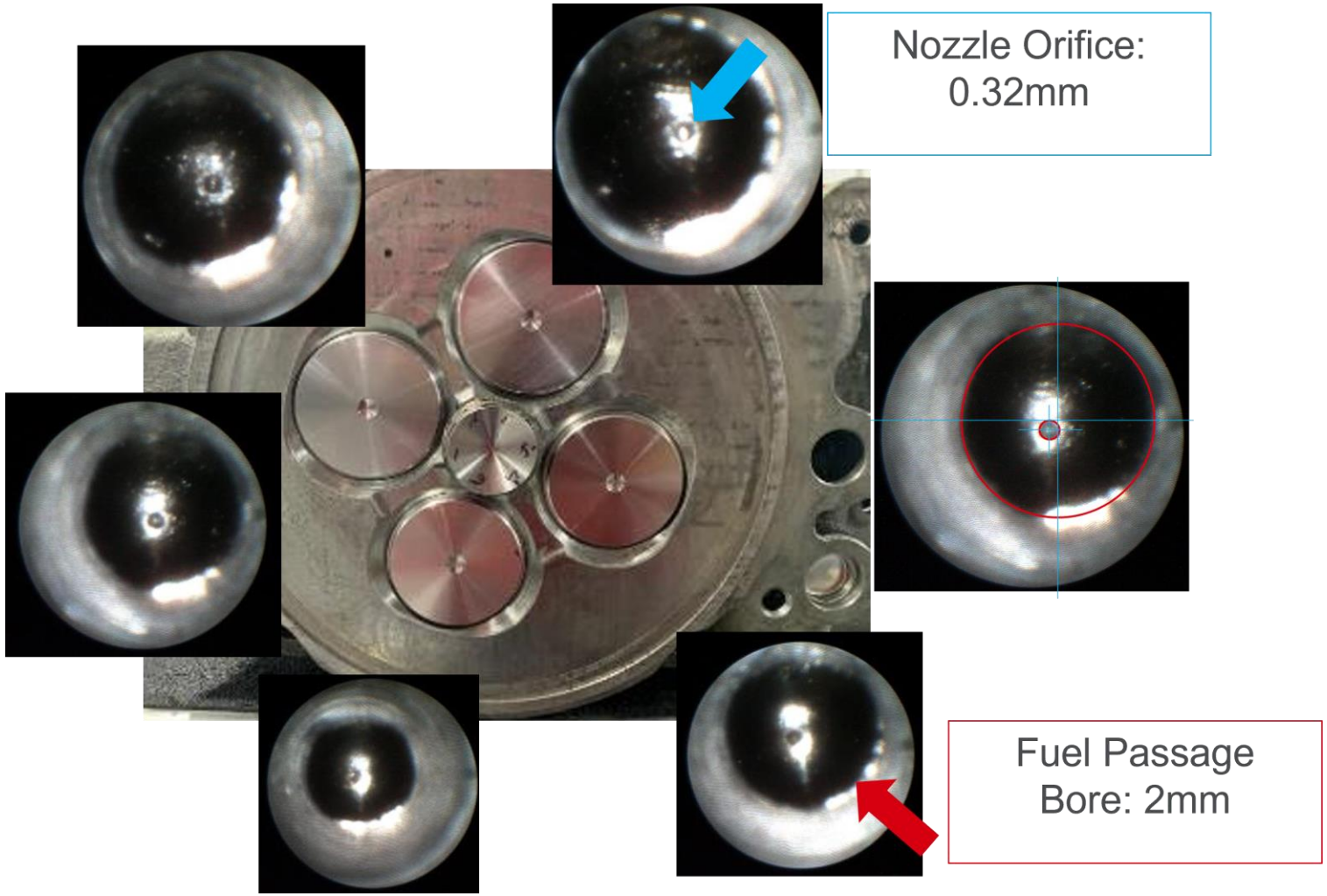


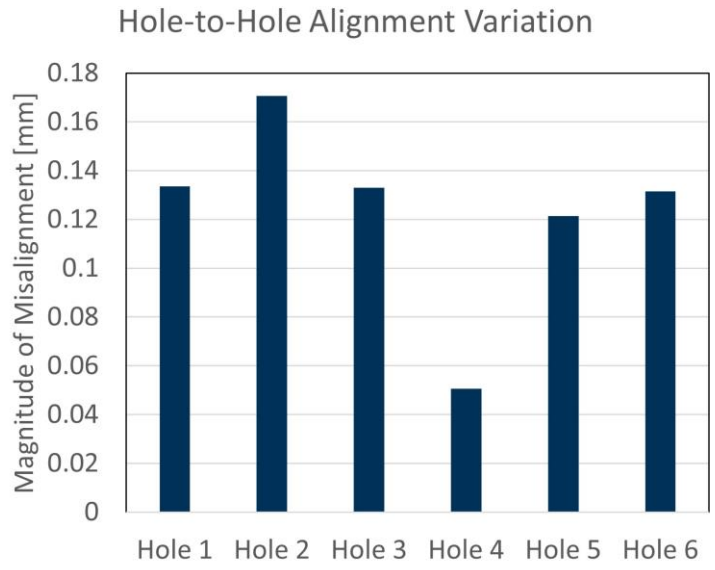
Nozzle 2: ~0.29mm orifice
Duty Cycle Emissions (Note: Mode 1 is estimated):
NOx: 6.76 g/kW-hr
Soot: 0.05g/kW-hr

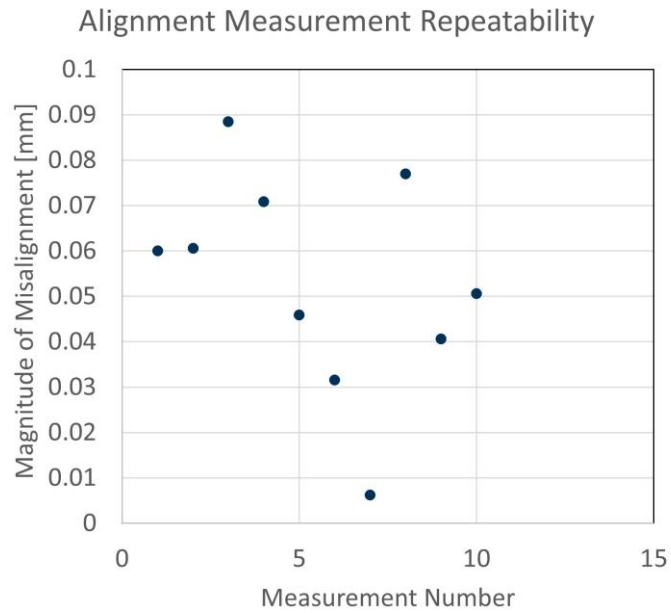
Comments:

- High soot/PM at low/med load, med/high speed
- Smaller injector orifice ➔ less PM

Technical Accomplishments and Progress: Misalignment Characterization





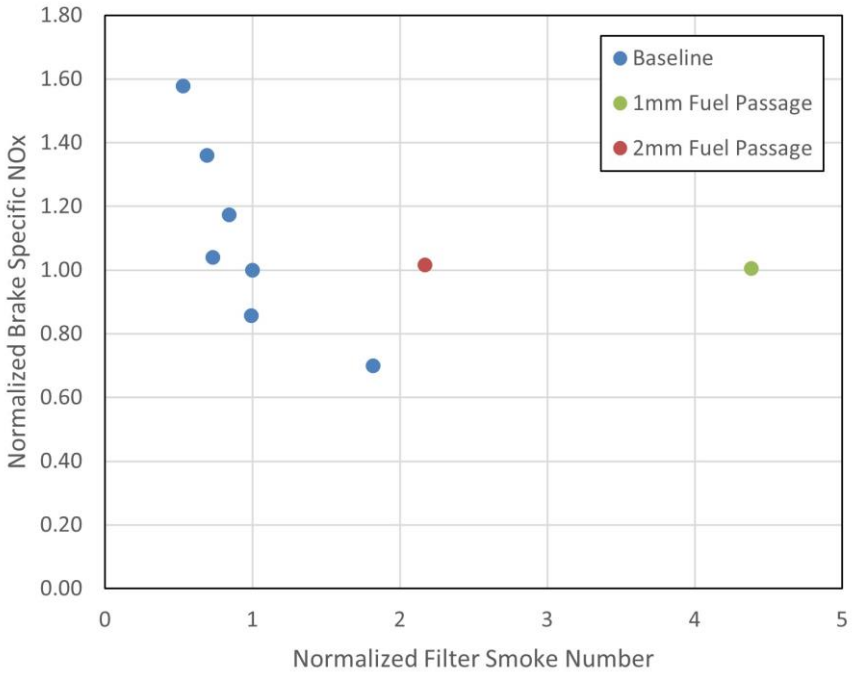


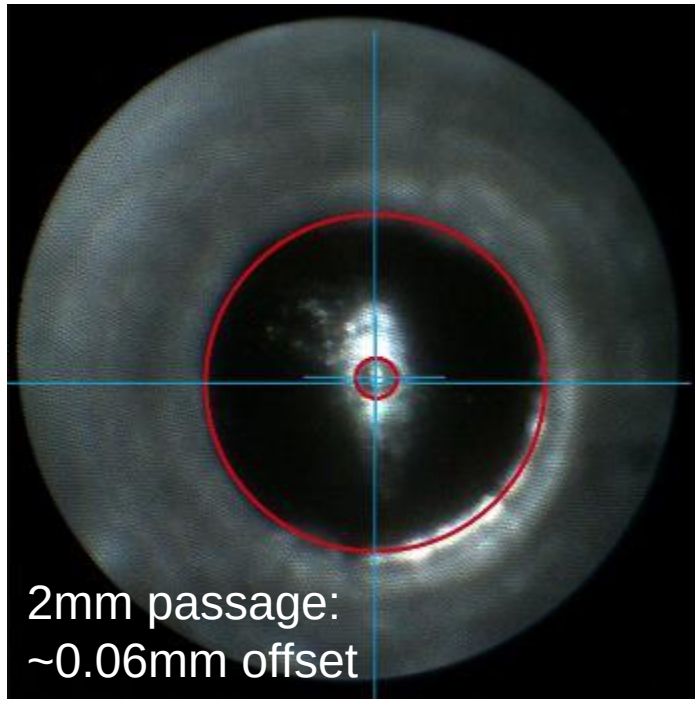
Measurement repeatability ±0.05mm, hole-to-hole variation ~0.07mm

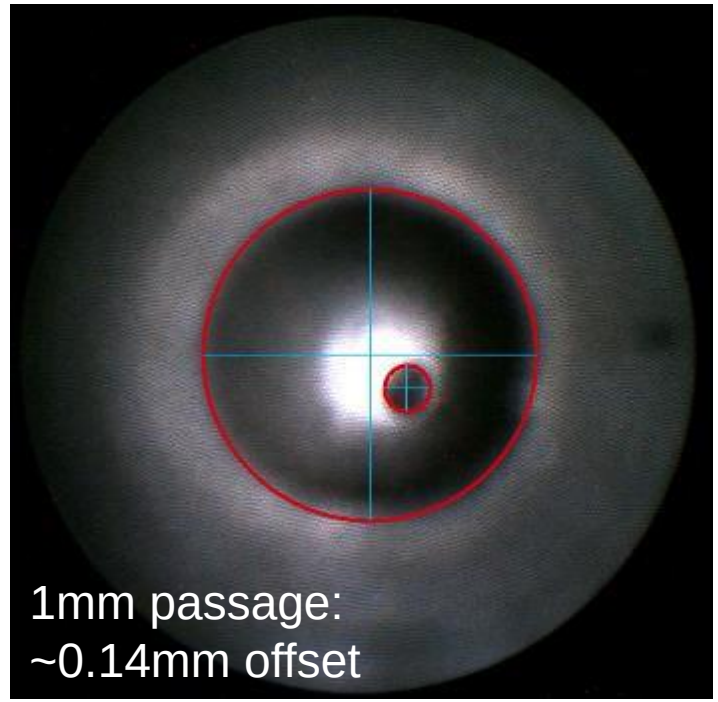
Technical Accomplishments and Progress: SCE Nozzle 1 Testing

0.32mm Injector Orifice

M5, 1200 RPM, 12bar BMEP







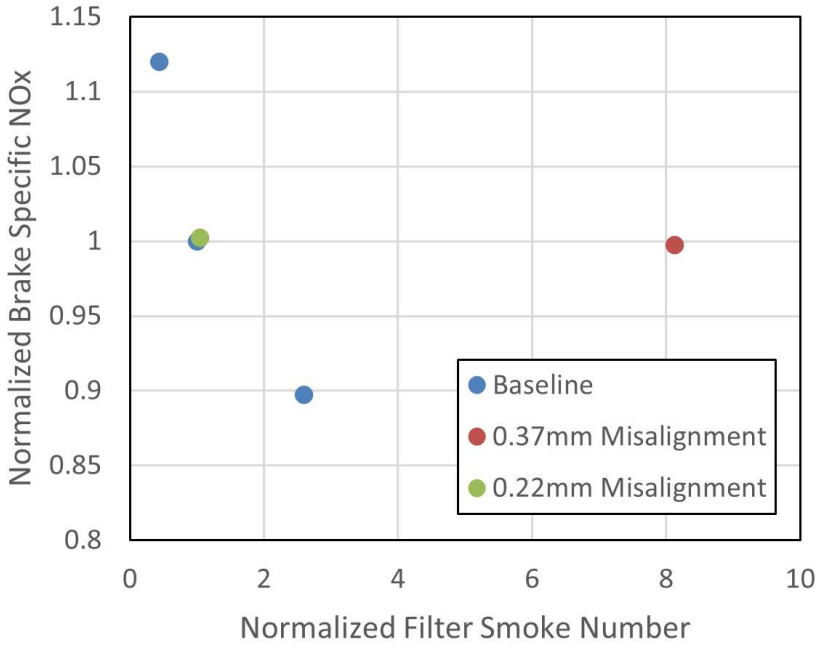
For the 0.32mm injector orifice, 1mm and 2mm fuel passages may be too small

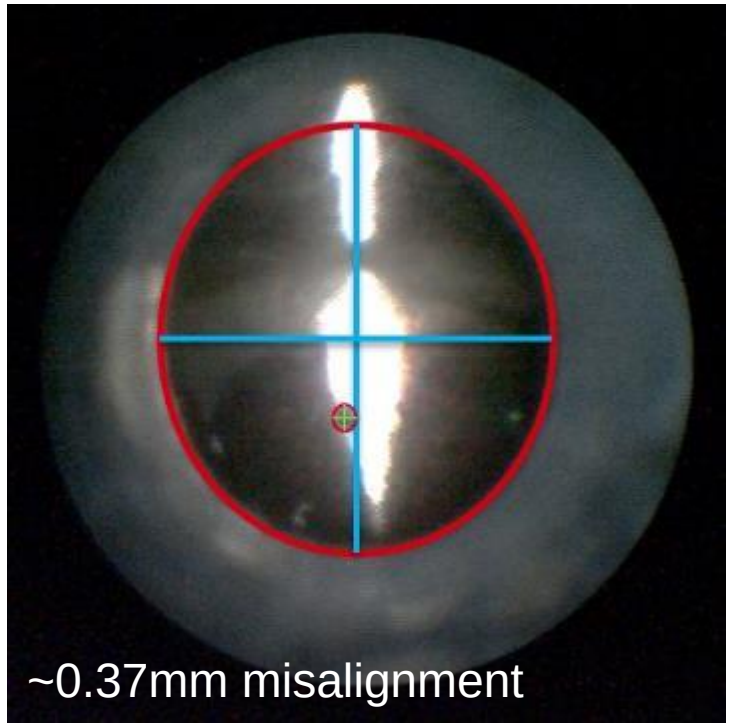
For 1mm fuel passage, alignment is very challenging

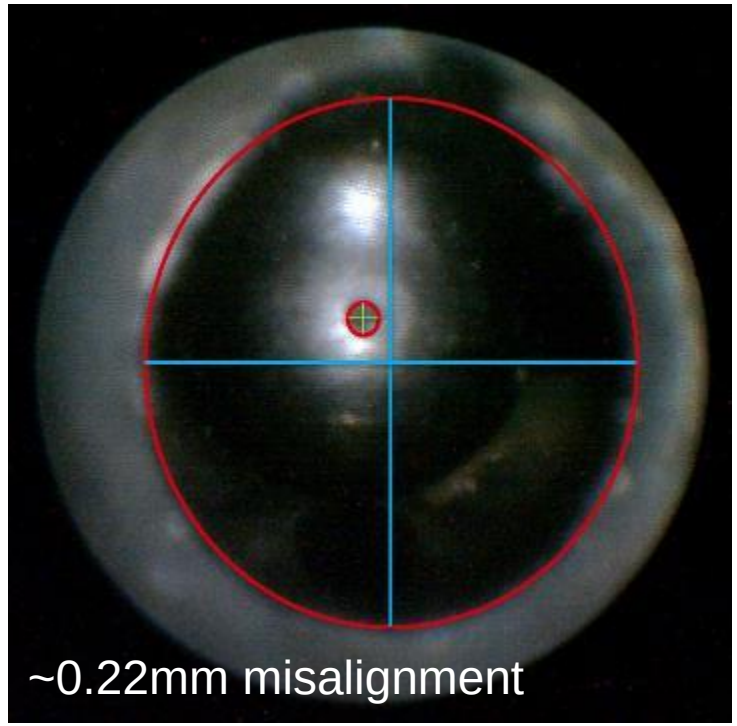
Technical Accomplishments and Progress: SCE Nozzle 2 Testing

~24bar BMEP, ~0.29mm injector orifice, 2mm fuel passage diameter

M8, 1500 RPM







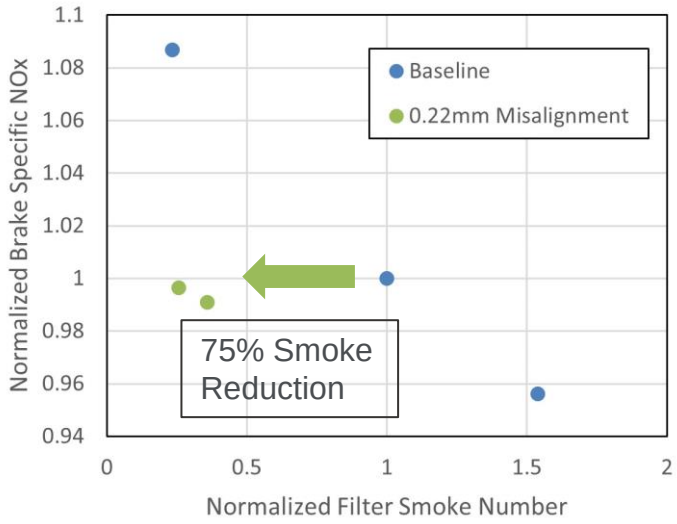
0.37mm misalignment led to 8X increase in FSN compared to either baseline or 0.22mm misalignment showed FSN parity

➔ Further alignment improvement may provide soot reduction

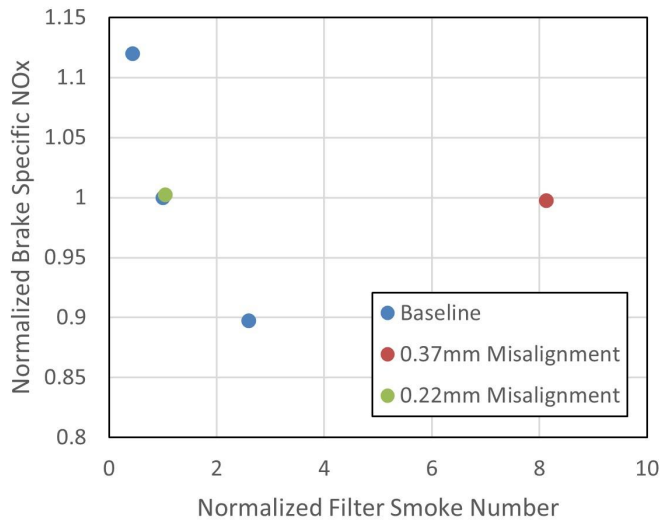
Technical Accomplishments and Progress: SCE Nozzle 2 Testing (Progress towards Go/No-Go 2)

~24bar BMEP, ~0.29mm injector orifice, 2mm fuel passage diameter

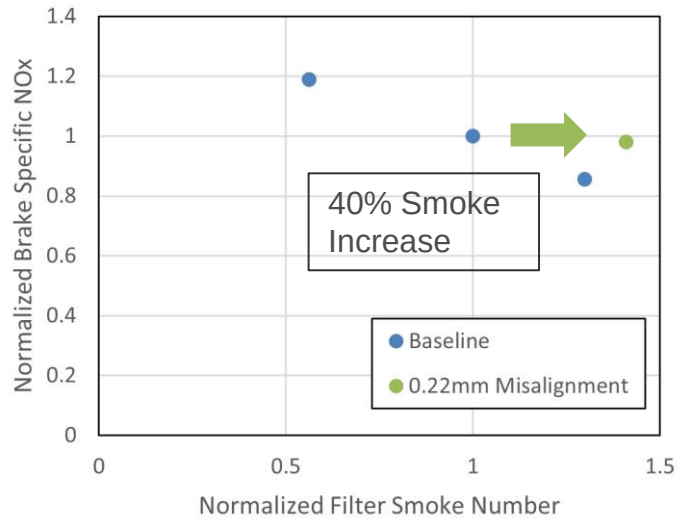
M2, 1200 RPM



M8, 1500 RPM



M10, 1800 RPM



75%FSN reduction for M2 (low speed) but 40% increase for M10 (high speed)

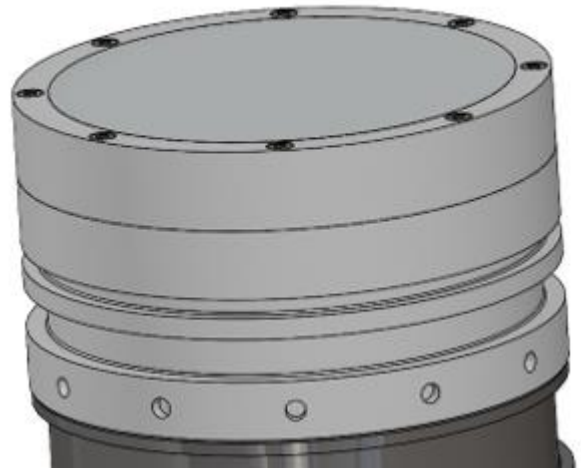
➔ CS showed a PM reduction at one condition, but parity/increase at other conditions

Collaboration with other institutions

- **Sandia National Laboratories (C. Mueller, C. Nilsen, G. Nyrenstedt, T. Gilbertson)**
  - Optical engine design modifications, testing
  - Biweekly discussions for planning/technical updates
  - Critical collaboration for applying DFI learnings to cooled spray design
  - Industry guidance/collaboration of national lab effort
- **Southwest Research Institute (T. Tinar, S. Ellis)**
  - Metal engine testing, combustion and emissions data collection

Remaining Challenges and Barriers

- **Optical Piston**
  - Sapphire window needs to be bonded to window holder
    - Soldering and brazing have been tried unsuccessfully
    - New brazing process and hardware designed
- **Hardware**
  - Prototype lead time is 2-3x what it was at start of project
- **DFI/CS Performance**
  - Continue to understand recommended geometric parameters for large injector orifices



Proposed future research

FY 22: Technology Characterization

- Evaluate multiple Cooled Spray designs on metal engine
- Downselect Cooled Spray geometry and test over engine map
- Optical engine measurements for Cooled Spray compared to DFI

FY 23: Meet Program Targets

- Additional hardware combinations to improve learnings/develop scaling laws
- 3-5 more CS/nozzle concepts
- 13-Mode evaluation of 2 hardware combinations

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

Summary Slide

- **Optical engine is operational up to part load**
  - Full load expected this quarter
- **First prototypes of Cooled Spray hardware have been tested**
  - Performance degradation with many hardware combinations/conditions
  - Performance improvement with some hardware combinations and conditions
  - Further iterations expected to improve performance over operating map

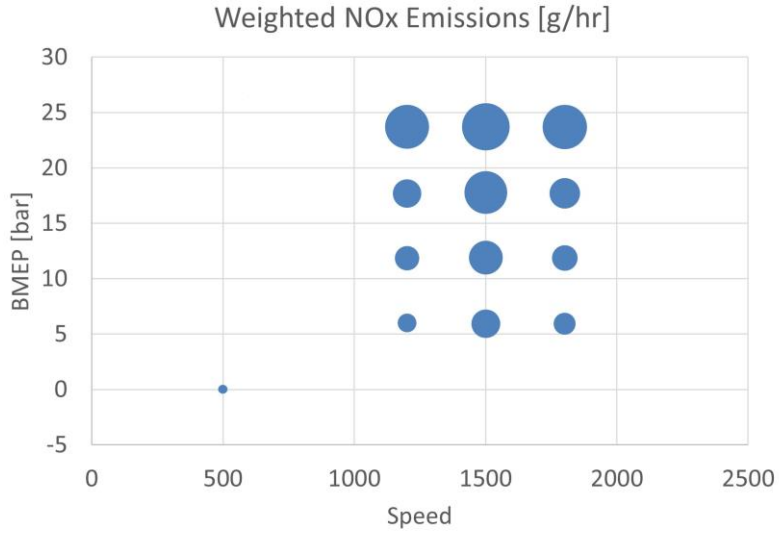
Technical Backup Slides (Optional, maximum of 5 slides)

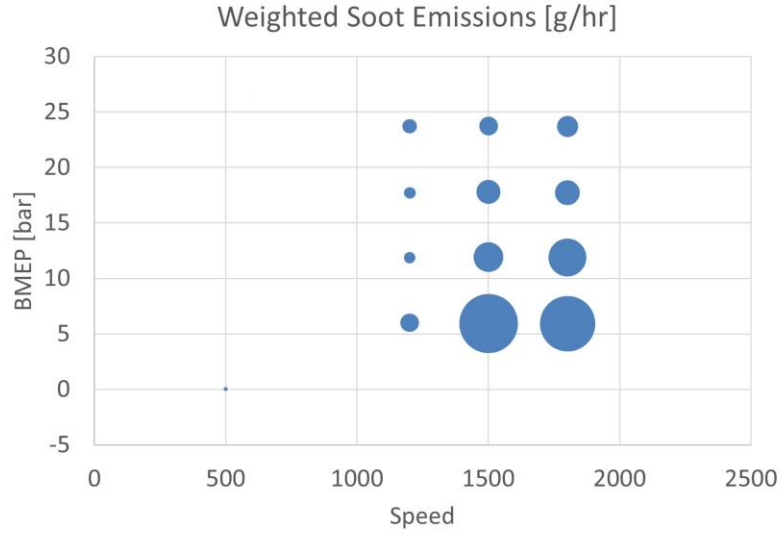
Progress: SCE Engine Baselining

Nozzle 1: 6-H, 0.32mm

Final Baseline
Nox: 6.72 g/kW-hr
Soot: 0.07g/kW-hr

Comments:
- High Nox at high load and also medium speed
- High soot/PM at low/med load, med/high speed

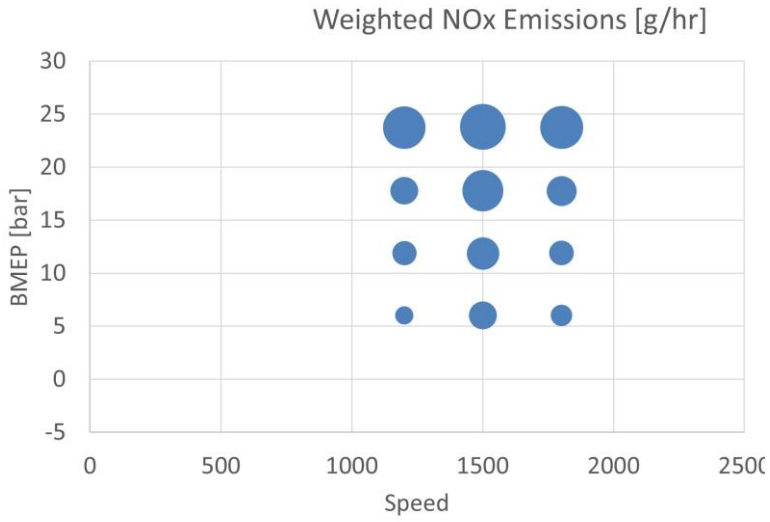


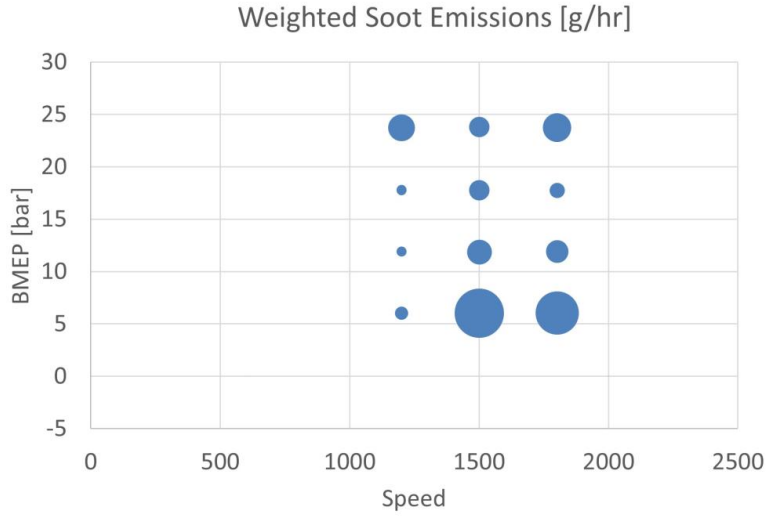


Nozzle 2: ~0.29mm Orifice

Final Baseline (Note: Mode 1 is estimated)
Nox: 6.76 g/kW-hr
Soot: 0.05g/kW-hr

Comments:
- Timing was adjusted for similar NOx
- Low PM in the mid-loads



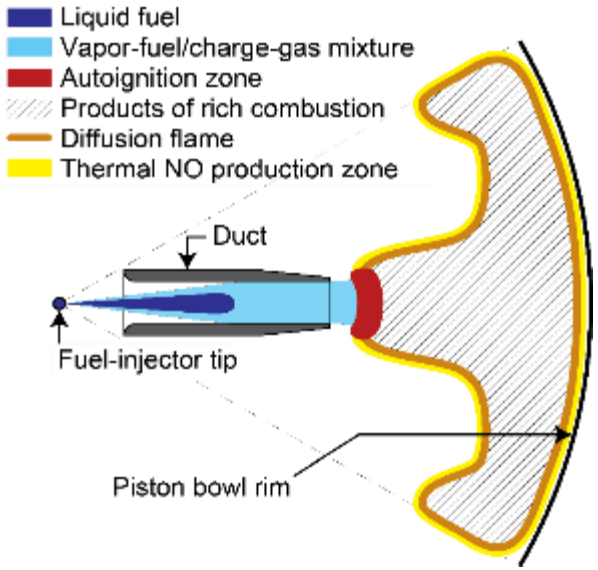


Relevance: What are the technologies?

Cooled Spray/Ducted Fuel Injection for Reduced Diesel Particulate Matter

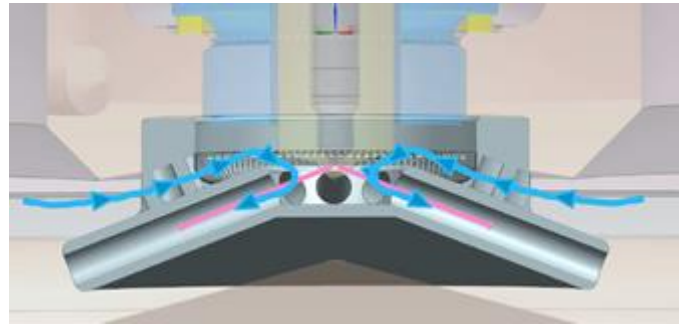
Ducted Fuel Injection:

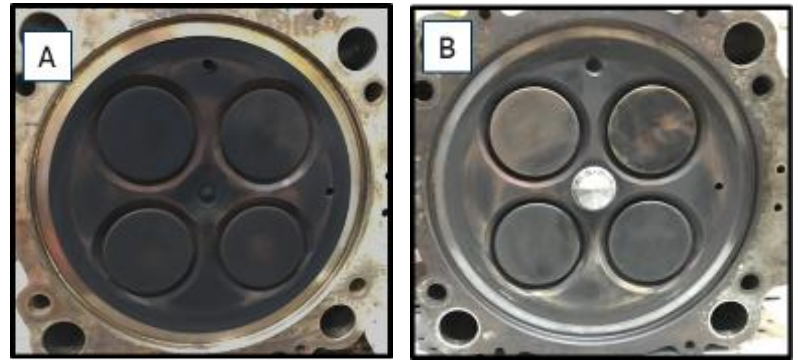
- Ducts placed outside of fuel injector nozzle orifice delay start of combustion
- Extend liftoff length
- Reduce formation of particulate matter



Cooled Spray:

- Monolithic insert installed in cylinder head
- Multiple fuel and air passages manage mixing of fuel and air
- Leads to lower particulate matter



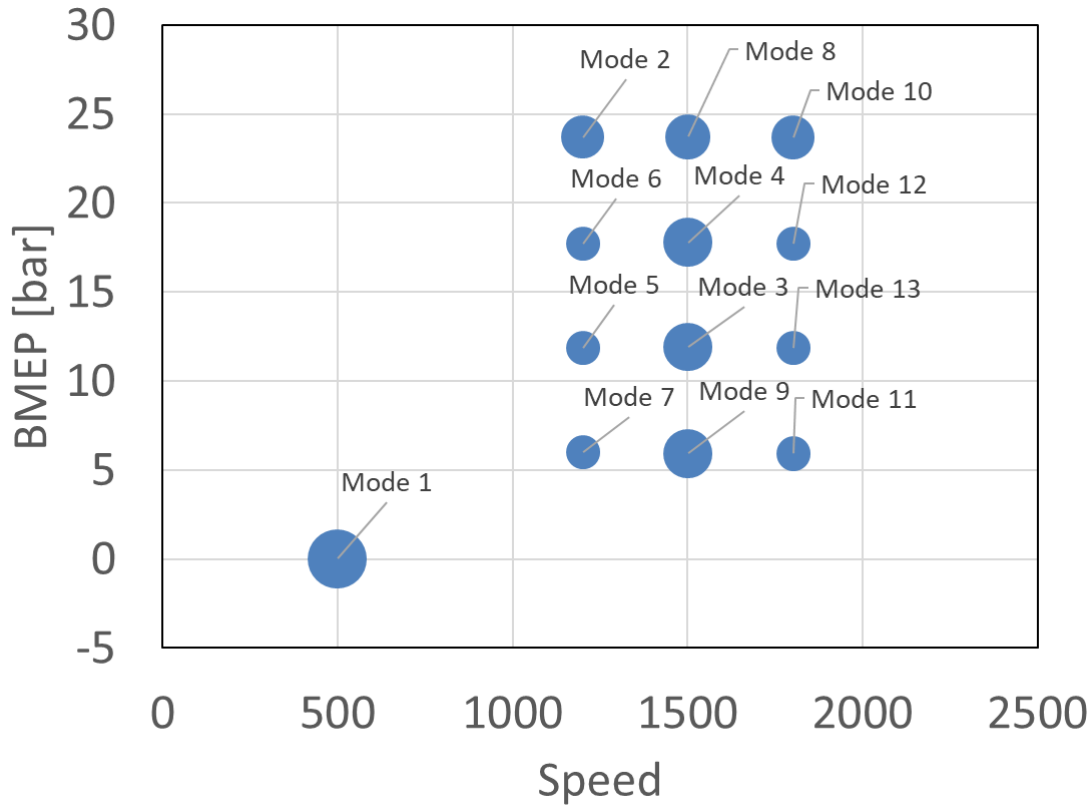


Compare Wabtec and Sandia Engines

Objective: Combustion in optical engine should be representative of combustion in the metal engine

		Sandia Optical Engine	Wabtec Metal Engine
Bore	mm	125	168
Stroke	mm	140	198
Compression Ratio		12.5	16
Displacement	L	1.72	4.4
Rated Speed	RPM	1800	1800
Rated Power	kW/Cyl	~52	155
Fuel System		Common Rail	Common Rail

13-Mode Supplemental Engine Test (SET)



Operating Conditions

- >20bar BMEP
- 1200, 1500, 1800RPM
- Engine boundary conditions being determined from GT-Power
- EGR: TBD based on engine performance with EGR (expect ~25-30%)