MAHLE

Powertrain

Next-Generation Ultra Lean Burn Powertrain
DE-EE0005656

Hugh Blaxill, PI

Michael Bunce, Presenter

MAHLE Powertrain, LLC

6/20/2014

Project ID: ACE087

Project Outline

MAHLE Powertrain

Timeline

Start Date: February 1, 2012

End Date: January 31, 2015

Percent Complete: 70%

Project Goals/ACE Barriers Addressed

- 45% thermal efficiency on a light duty SI engine with emissions comparable to or below existing SI engines *(A, B, C, D, F)*
- 30% predicted drive cycle fuel economy improvement over comparable gasoline engine vehicle *(A, C, H)*
- Cost effective system requiring minimal modification to existing hardware *(G)*

Budget

Contract Value (80/20): $ 3,172,779

Gov't Share:	$	2,499,993
MPT Share:	$	672,796

Funding received in FY2013: $ 494,361

Funding for FY2014: $ 299,618

Partners & Subcontractors

Ford – Test engine platform

DELPHI – Custom injector design and development

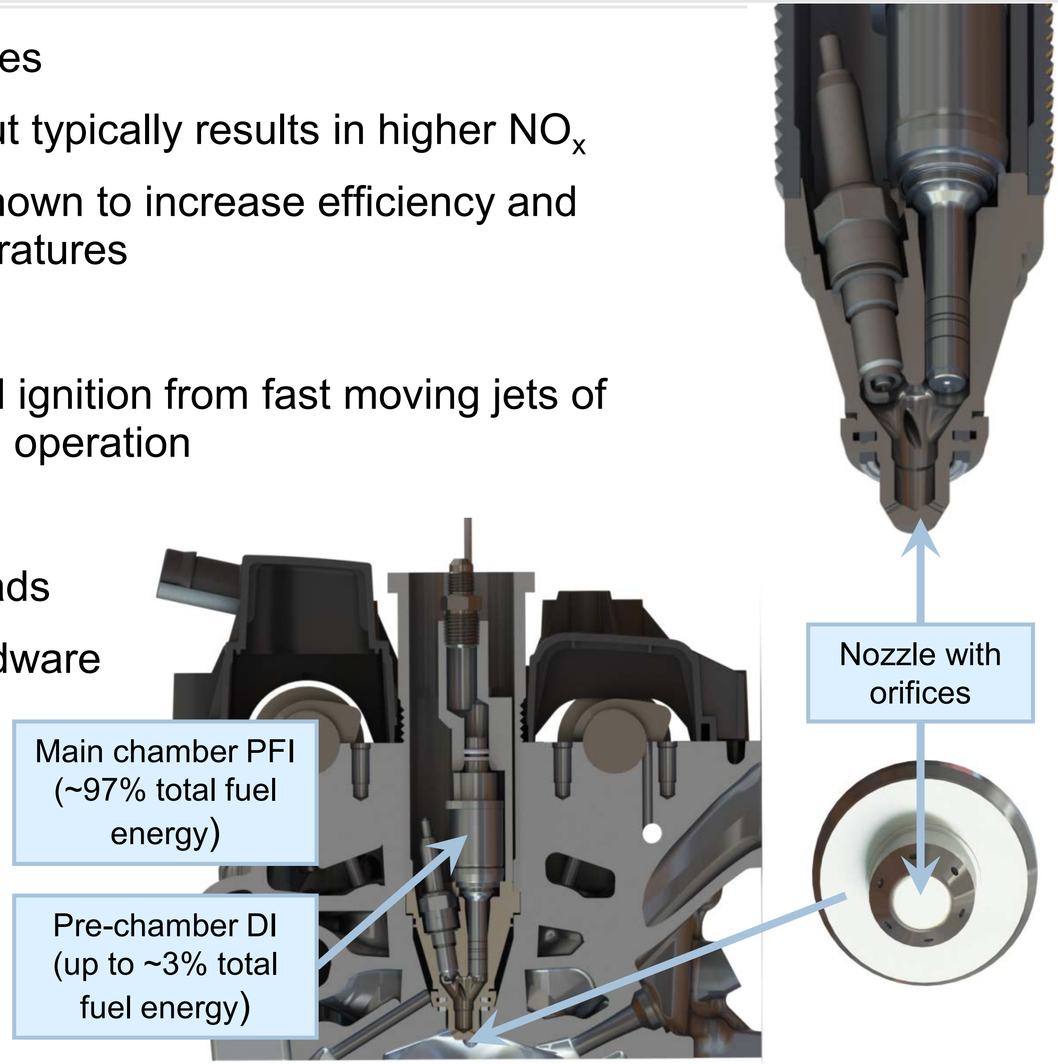
Background

MAHLE Powertrain

- Demand for highly efficient and clean engines
  - Lean operation increases efficiency but typically results in higher NO_x
  - Ultra lean operation ($\lambda > 2$) has been shown to increase efficiency and reduce NO_x due to low cylinder temperatures

- Turbulent Jet Ignition (TJI) offers distributed ignition from fast moving jets of burned/burning products enabling ultra lean operation
  - Low NO_x
  - Increased knock resistance at high loads
  - Simple integration into production hardware

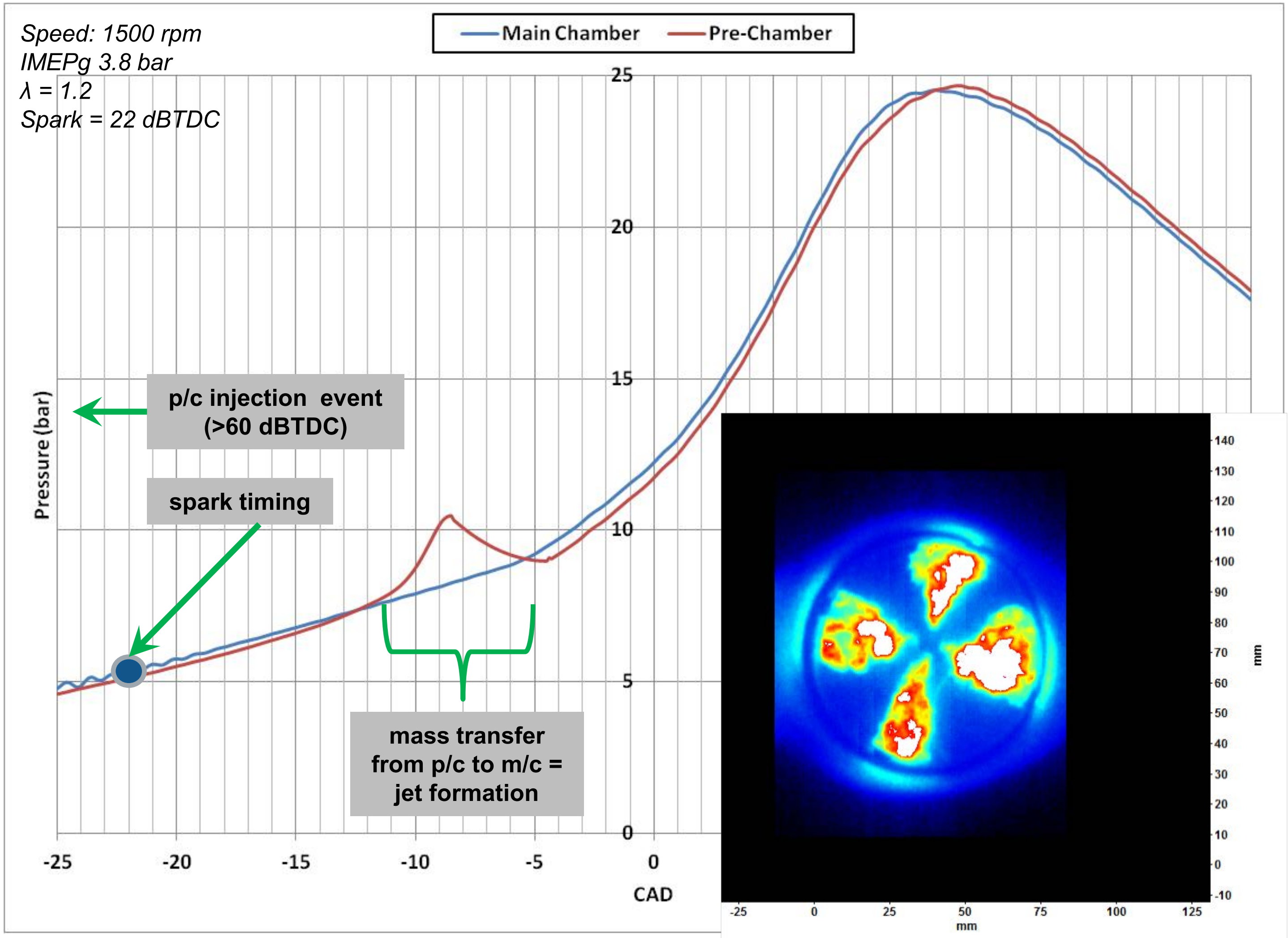
- Enabling technologies
  - TJI + Boosting



Turbulent Jet Ignition Overview

MAHLE Powertrain

- Auxiliary fueling event enables effective decoupling of pre/main chamber air-fuel ratios
- Thermal efficiency benefit of TJI
  - Ultra-lean operation
  - Reduced throttling losses
- Boosting can enable map-wide lean/ultra-lean operation
  - Multiple operating strategies/platforms possible

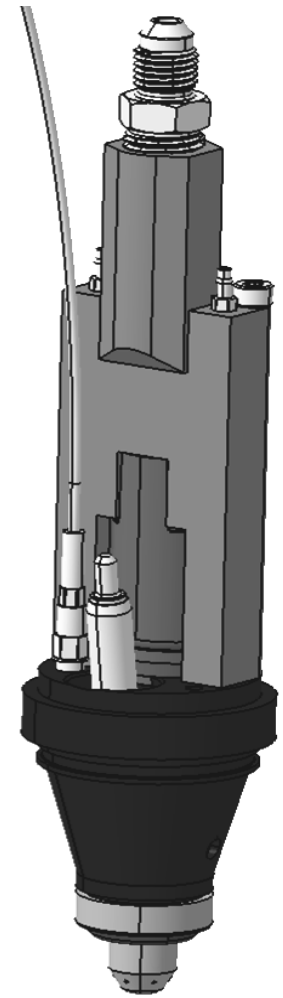


Objectives/ACE Barriers

MAHLE Powertrain

- Objectives:
  - Utilize TJI to achieve stated project goals
    - 45% thermal efficiency
    - 30% vehicle drive-cycle fuel economy improvement over baseline
    - Emissions comparable to baseline; minimal modifications to engine
  - Increase understanding of TJI performance sensitivity to design and operating conditions

- Barriers Addressed:
  - (A) Fundamental understanding of an advanced combustion technology
  - (B) Emissions reductions may enable reduced cost emissions controls
  - (C) Develop tools for modeling advanced combustion technology
  - (F) Produce emissions data on an advanced combustion engine
  - (G) Prioritize low cost and ease of integration
  - (H) Provide comparable levels of performance to existing SI engines



Phase 1 Approach

MAHLE Powertrain

- **Optical Engine Testing** → Jet velocity as a function of TJI hardware
- **Single Cylinder Metal Engine Testing** → Efficiency/emissions as functions of jet velocity
- **1-D and 3-D simulations** → Validation of experiments, helps drive design optimization

Budget Phase 1

TJI design optimization

Phases 2 and 3 Approaches

MAHLE Powertrain

- Boosted Single Cylinder Metal Engine Testing → Fuel injection timing/quantity and spark timing sweeps → **Budget Phase 2**
- 3-D simulations → Validation of experiments → **Budget Phase 2**

Budget Phase 2
TJI design validation, operating parameterization

- Boosted Multi-Cylinder Metal Engine Testing → Mini-map generation provides input to 1-D simulation → **Budget Phase 3**
- 1-D simulations → Predict TJI vehicle drive cycle fuel economy improvement → **Budget Phase 3**

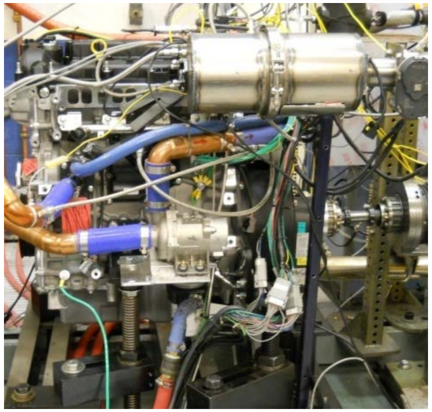
Budget Phase 3
Map generation and drive cycle simulation

Milestones and Accomplishments Since 2013 AMR

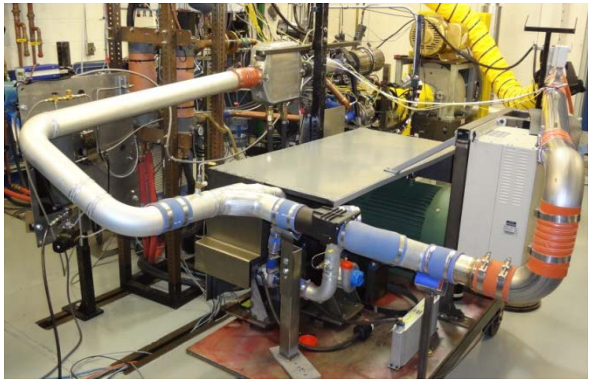
MAHLE Powertrain

- Completed (Budget) Phase 1
  - Completed testing of single cylinder metal engine, focusing on nozzle design optimization
- Completed (Budget) Phase 2A
  - Single cylinder metal engine with addition of boost rig
    - Testing focused on pre-chamber design optimization
    - Preliminary operating strategy investigation
  - Initiated CFD model correlation to experimental data

Milestones	Completion Date
BP1	
Milestone 1 – Phase 1 Design Work Complete	07/25/12
Milestone 2 – Component Procurement Complete	10/30/12
BP2	
Milestone 3 – Single-cylinder Engine Testing Complete	06/04/13
Milestone 4 – Phase 1 Research Completion	08/10/13
Milestone 5 – Boosted Single Cylinder Engine Shakedown Complete	10/30/13
Milestone 6 – Boosted Single Cylinder Engine Optimization and Vehicle Fuel Economy Prediction Complete	07/01/14
Milestone 7 – Phase 2 Complete	07/15/14
BP3	
Milestone 8 – Boosted Multi-Cylinder Engine Build and Shakedown Complete	09/12/14
Milestone 9 – Boosted Engine Optimization and Vehicle Fuel Economy Prediction Complete	11/20/14
Milestone 10 – Project Complete	01/31/15



Single-cylinder metal engine (Phases 1 and 2)

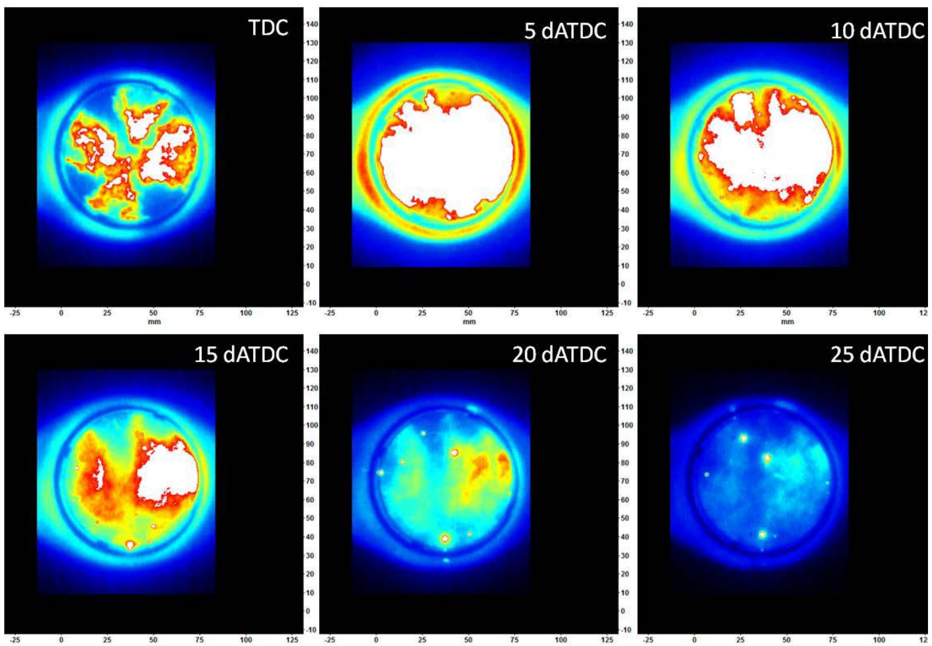


MPT boost rig (Phase 2)

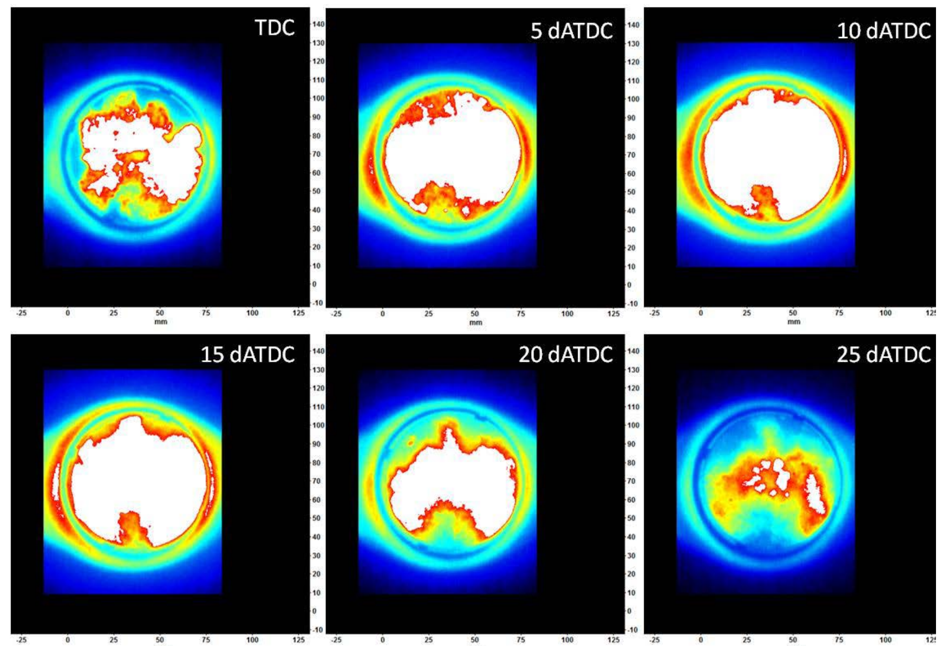
Phase 1 Optical Engine Results

- Shorter burn duration correlates to smaller orifice area (confirmed with metal engine)
- Reducing orifice area a major lever to increase velocity
  - Jet velocity correlates to degree of jet penetration prior to ignition
  - Targeted velocity prevents impingement on wall

Design 4 – normalized orifice area = 1.24



Design 5 – normalized orifice area = 2.48

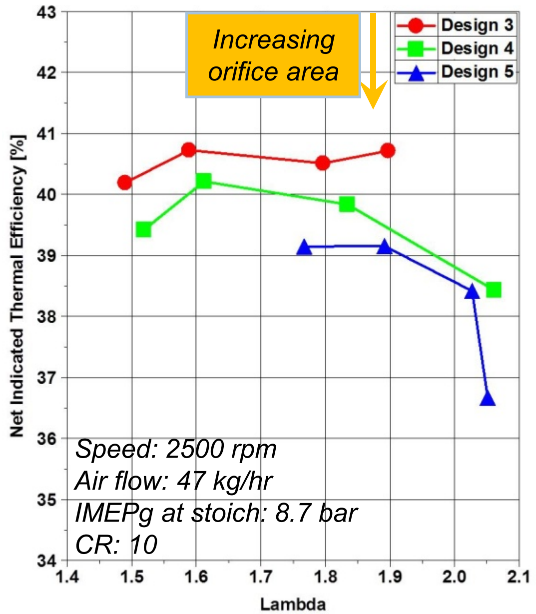


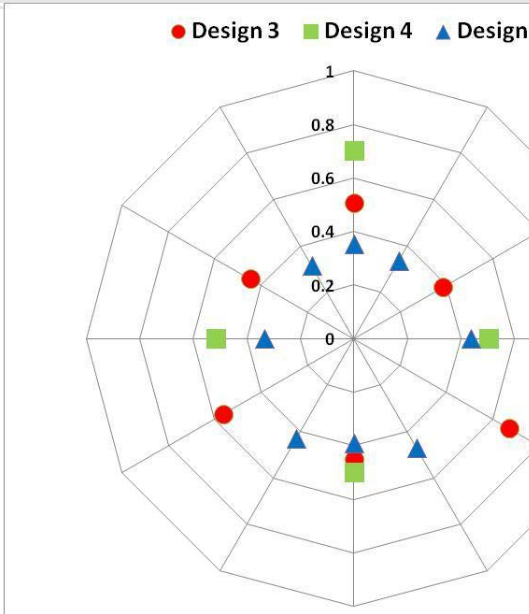
Phase 1 Analysis of Optical and Metal Engine Data

MAHLE Powertrain

- Small orifice area → short burn duration → high net thermal efficiency

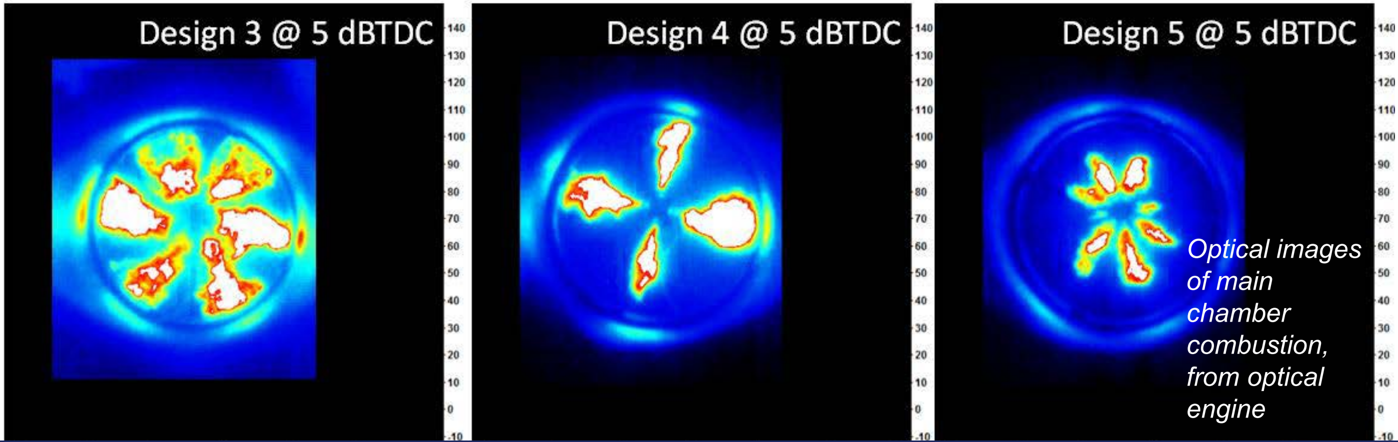
- Short burn duration is associated with:
  - Enhanced distribution of ignition sites
  - Short flame travel distance





Ignition site distance from bore center, from optical engine

- **Conclusion:** Jet velocity and ignition site distribution targeting through nozzle geometry to optimize NTE



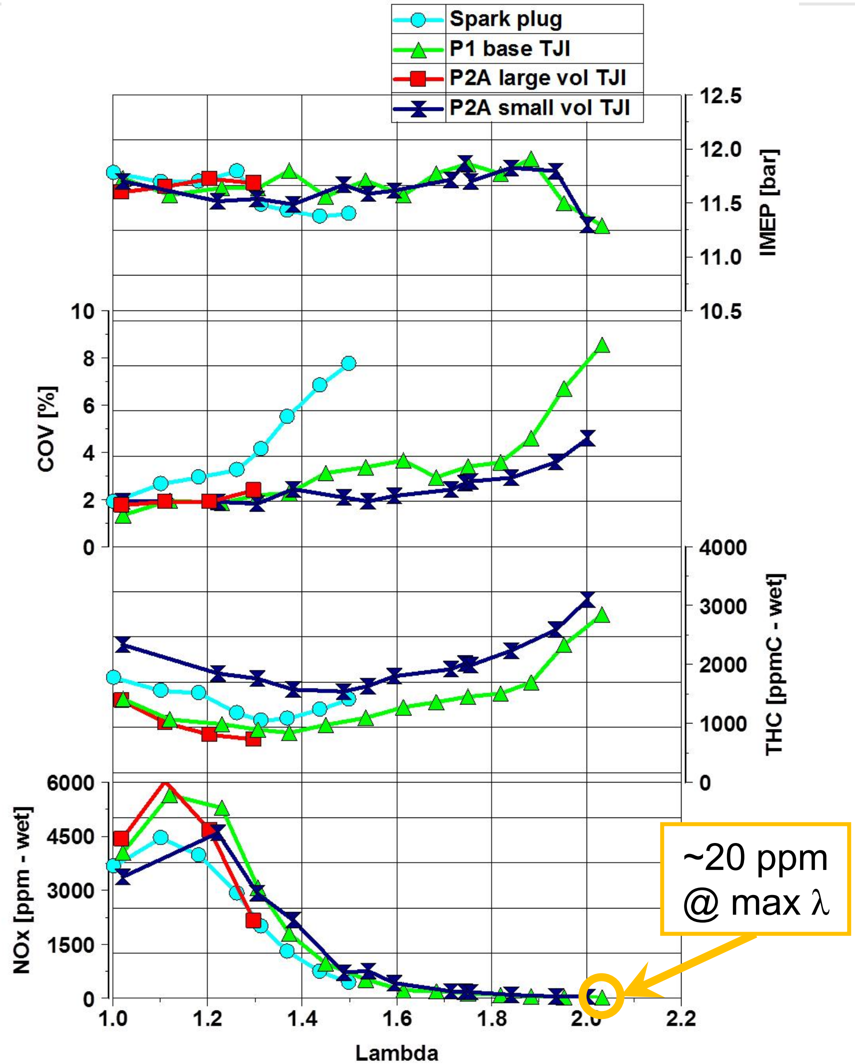
Optical images of main chamber combustion, from optical engine

Phase 2A Engine Results

MAHLE Powertrain

- Addition of boost rig and back pressure valve to emulate turbocharger
  - Maintain constant load during lambda sweep
  - Goal: emulate corresponding NA engine speed/load curve regardless of lambda
- Data shows performance differences among pre-chamber designs
- Area of interest: 1.7 < λ < 2.0
  - Acceptable combustion efficiency and COV
  - NOx < 100ppm

Speed: 2500 rpm
IMEPg: 11.7 bar
CR: 14

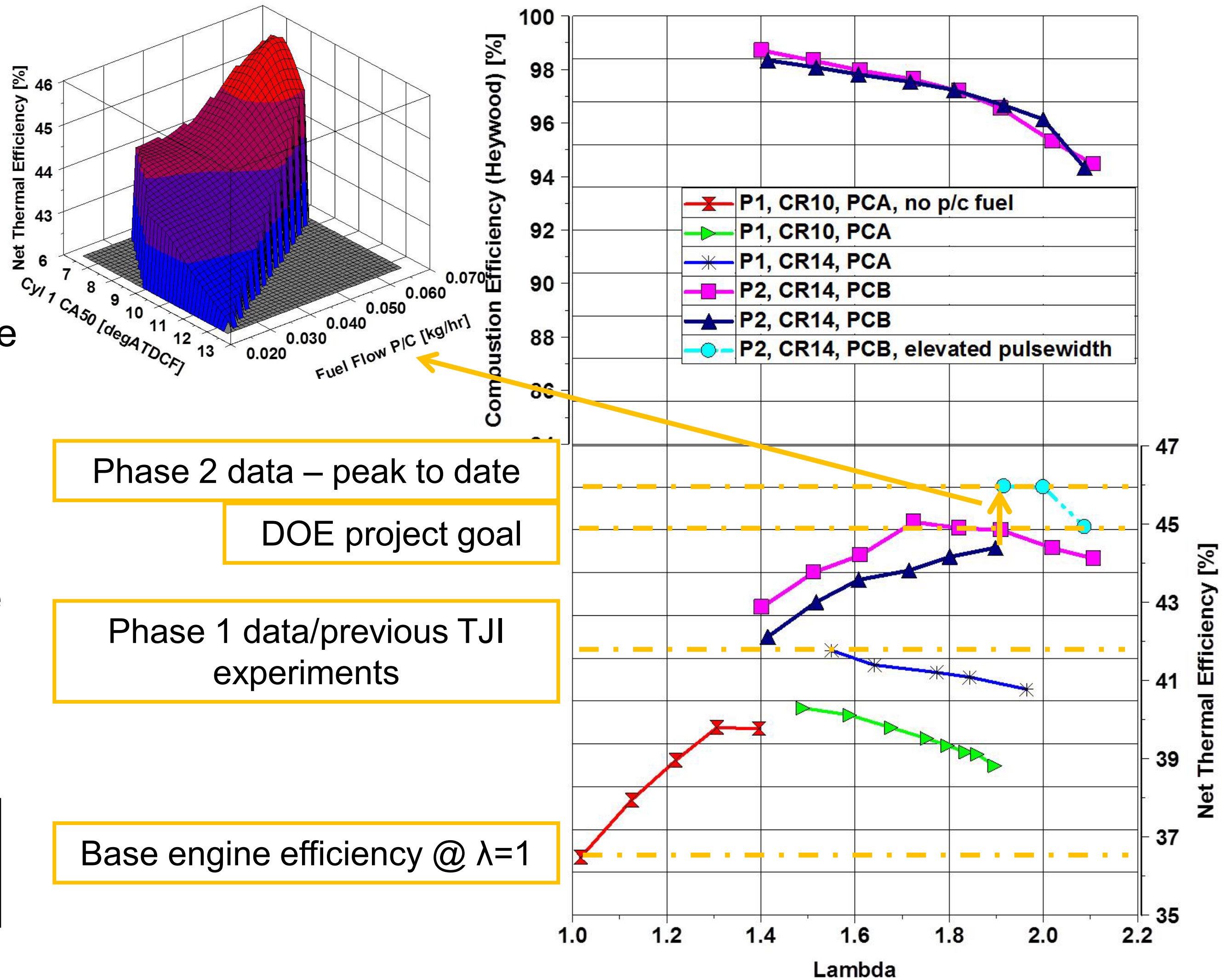


Phase 2A Engine Results

MAHLE Powertrain

- Promising p/c and nozzle designs tested further
  - Preliminary operating strategy investigation
- Data suggests TJI can achieve 45% net thermal efficiency
  - Relationship between added p/c fuel, jet strength, and m/c HRR
  - Primary project objective met

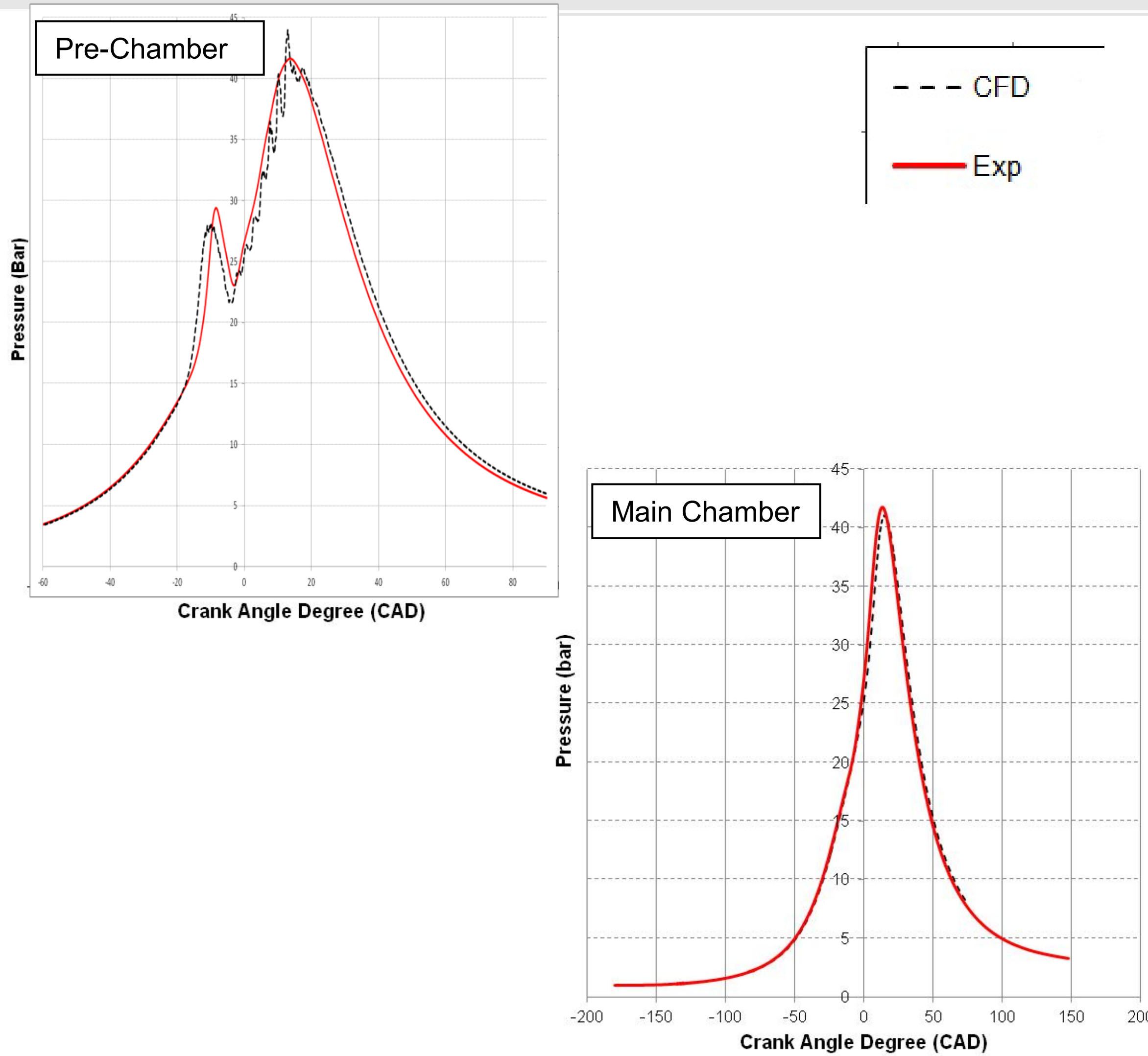
Speed: 2500 rpm
Phase 1 IMEPg: 8.7 bar, WOT, airflow-limited
Phase 2 IMEPg: 11.7 bar, WOT



Numerical Simulation Activities and Progress

MAHLE Powertrain

- CFD modeling:
  - Correlate CFD simulation to experimental data
  - Model outcome is used for further refinement of the model
  - Model to be used as explanatory tool to help guide design optimization

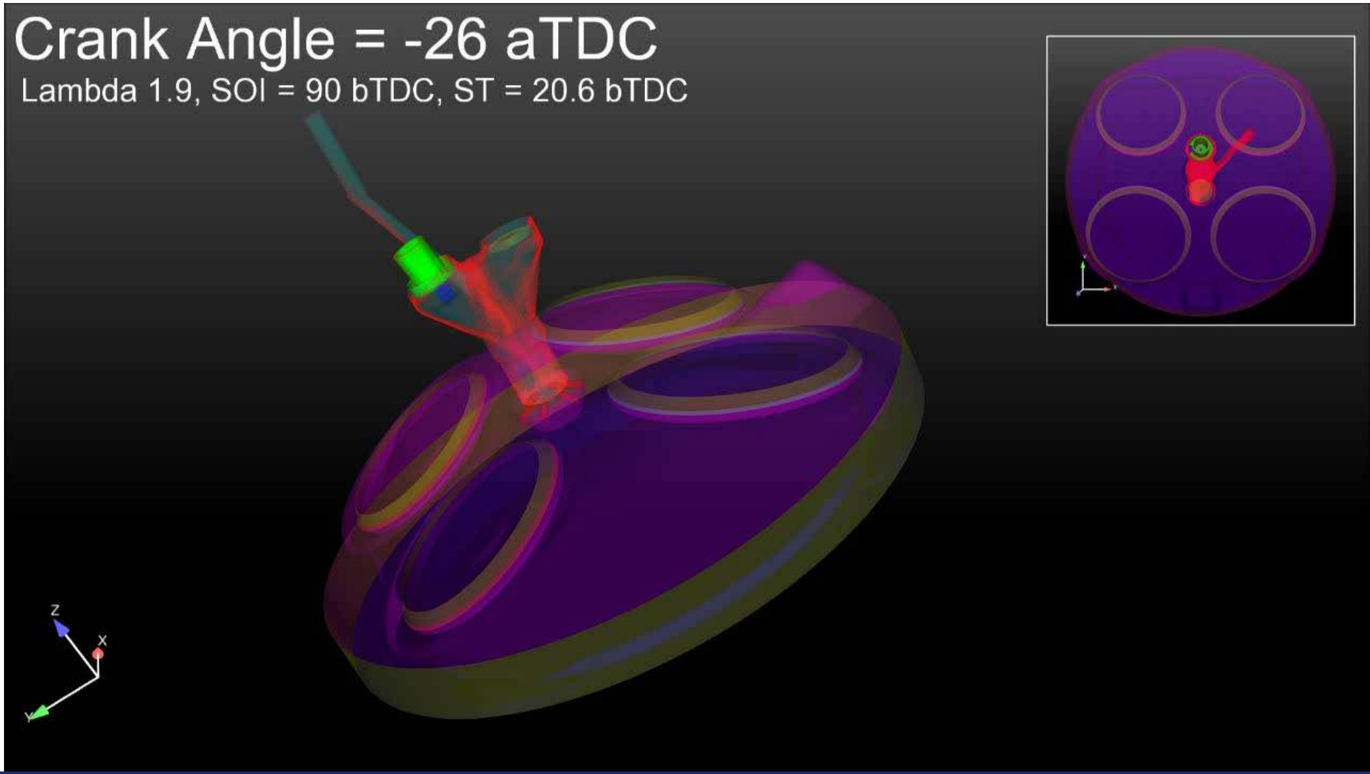


- Progress made:
  - Strong correlation between model and experiment for multiple auxiliary fueled conditions
  - Non-auxiliary fueled model under development

Correlated Fueled Pre-Chamber Simulation

MAHLE Powertrain

- Iso-surface temperature (1500 K)
- Main chamber combustion primarily controlled by:
  - Pre-chamber combustion event
  - Nozzle geometry
- Multiple, distributed ignition sites
- Gas exchange resonance between chambers



Response to Previous Year Reviewers' Comments

- **Multiple comments concerning characterization of AFR in pre-chamber**
  - "The project needs further application of research tools to characterize the internal jet pre-chamber…net air to fuel ratio (AFR)."
  - "…progress related to understanding the AFR…(is) needed."
  - RESPONSE: Delphi CFD and internal CFD provide uncorrelated information about AFR stratification vs. crank angle. MPT will attempt experimental in-pre-chamber measurement to determine AFR in Phase 2B in conjunction with Delphi and Cambustion
    - Procedure developed by Delphi for typical cylinder volumes
    - Pre-chamber volume <2% of main combustion chamber volume
- **Multiple comments expressing concerns over cold start ability**
  - "…program should address issues such as: low temperature cold start, which has been problematic for…pre-chamber systems."
  - "…reviewer expressed some concerns with cold start and warm-up operation…"
  - RESPONSE: Cold start development program out of scope of project, however MPT and Ford will study "cold start-ability" testing of multi-cylinder TJI engine
    - Will investigate multiple operating strategies and hardware configurations

Collaborations

- **Ford Motor Company** – Project Partner
  - Donated engine hardware, offered operational advice on optical engine, will participate in data sharing
- **Delphi Corporation** – Project Subcontractor
  - Supplied pre-chamber fuel injectors and are conducting CFD analysis on fuel injection characteristics
- **Spectral Energies LLC** – Project Subcontractor
  - Acquired optical engine data, contributed to post-processing
- **University Collaboration**
  - Engaged multiple universities concerning further TJI investigation

Upcoming Project Work and Challenges

MAHLE Powertrain

Key Challenges

- Challenge: Achieving 30% vehicle drive-cycle fuel economy improvement with TJI
  - Multi-cylinder TJI engine testing is necessary to determine accurate brake specific fuel consumption
- Challenge: Development of TJI operating strategy
  - An appropriate operating strategy is necessary to translate positive thermal efficiency results into real-world fuel economy savings across the operating map
    - Spark timing, auxiliary fuel injection pressure/timing/quantity, valve timing, etc.
  - Provide understanding of the limitations of TJI application across the operating map

Future Work

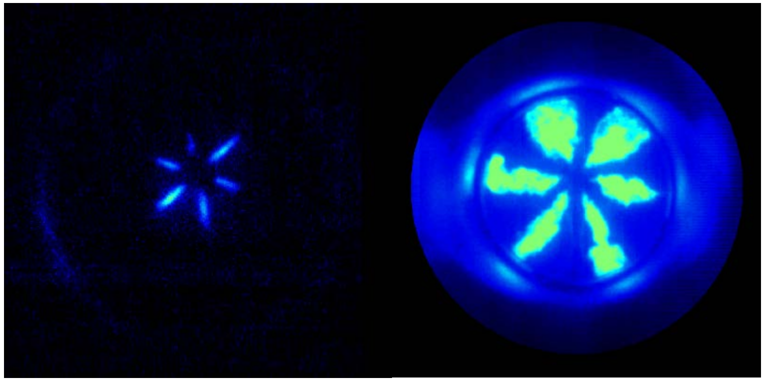
- Phase 2B:
  - Complete Phase 2B engine testing
    - Complete design optimization
    - TJI operating strategy development
    - In-pre-chamber RGF and AFR determination
  - Complete CFD model correlation to non-fueled experimental data
- Phase 3:
  - Multi-cylinder engine build and installation
  - Complete multi-cylinder engine testing
    - Mini-map generation
  - Complete 1D vehicle drive-cycle analysis

Phase 1 and Phase 2A Summary

MAHLE Powertrain

- Phase 1 design optimization of nozzle successful
  - Better understanding of relationship among jet characteristics, combustion, and NTE
- Phase 2 pre-chamber design optimization and operating strategy development ongoing
  - Correlated CFD as explanatory tool for empirical design optimization
  - Map-wide operating strategy to drive 1D cycle fuel economy results
- Developed TJI design and preliminary operating strategy capable of achieving 46% net thermal efficiency
  - Exceeds primary project objective

Project Goal	Phase Accomplished	Status
Minimal modifications to engine design	Phase 1	achieved ✓
45% peak thermal efficiency	Phase 2	exceeded ✓
Emissions comparable to baseline	Phase 3	work ongoing
30% vehicle drive-cycle fuel economy improvement over baseline	Phase 3	work ongoing



MPT would like to acknowledge DOE Office of Vehicle Technologies for funding this work.

Powertrain

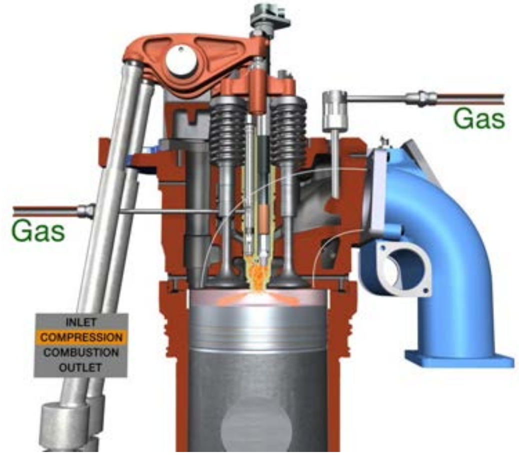
Thank you for your attention

Technical Back Up Slides

Turbulent Jet Ignition Overview

- Pre-chamber combustion concepts are not new
  - Ricardo "comet combustion pre-chamber" – 1920s
  - Applied to SI engines as a lean combustion enabling technology
    - Investigated by many OEMs – Honda, VW, etc.
  - Currently in production in large-bore CNG gensets

- TJI is an innovative approach to the pre-chamber concept
  - Auxiliary pre-chamber fueling using prototype low-flow DI injector
    - Enables spray targeting, precise metering
  - Small volume pre-chamber = Small auxiliary fuel requirement
  - Small nozzle orifice diameter promotes flame quenching
    - Jet penetration into main chamber before re-ignition
  - Multiple orifices result in distributed ignition



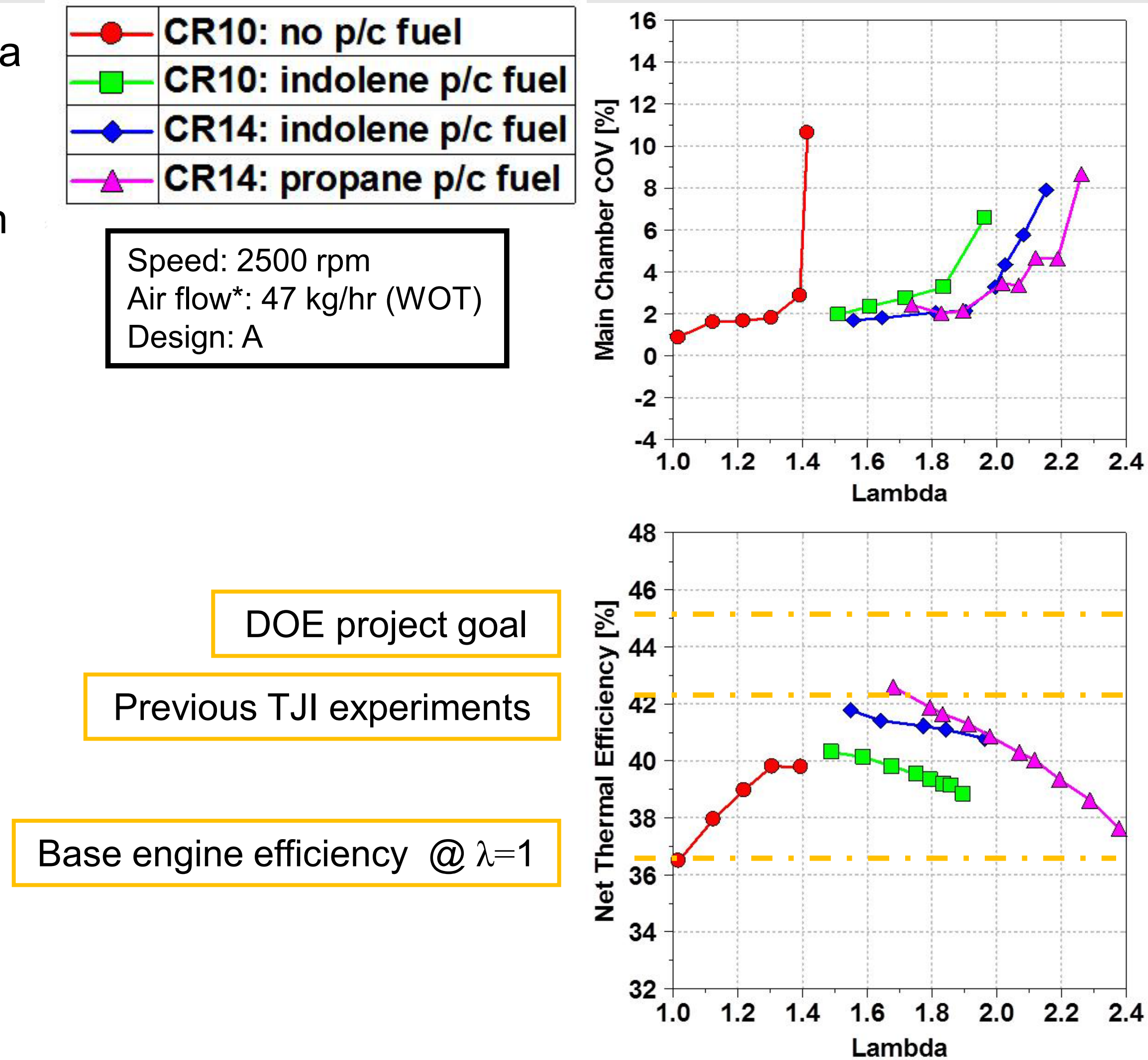
Wartsila SG


Turbulent jet igniter

Technical Accomplishments

Phase 1 Metal Engine Results

- TJI effectively extends the lean limit of a standard SI engine by maintaining stable combustion
  - Enables ultra-lean (λ>2) operation
- Results demonstrate:
  - Significant thermal efficiency gain over base engine
  - Results comparable to previous TJI experiments
  - Thermal efficiency taper due to changing load



Note: 47 kg/hr = 8.7 bar IMEPg @ stoich

Technical Accomplishments

Fueled Pre-Chamber: Gas Exchange